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Die Arbeiten können in deutscher, englischer oder französischer Sprache erscheinen. Es soll ihnen eine Zusammenfassung in mindestens zwei Sprachen vorangestellt werden. Eine Zusammenfassung ist auf jeden Fall vom Verfasser mitzuliefern, ihre Übersetzungen werden nötigenfalls vom Verlag besorgt. Die Literaturhinweise erfolgen durch im laufenden Text in Klammern eingefügte Nummern, die genaue Zitate bezeichnen, die in einem Literaturverzeichnis am Ende der Arbeit zusammenzustellen sind.

Fortsetzung auf der III. Umschlagseite

Internationales Symposion für experimentelle Meteorologie

Colloque international de Météorologie expérimentale

International Symposium on Experimental Meteorology

Zürich 4. bis 6. Oktober 1954

Opening Address.

At the instance of the Division of Agriculture of the Federal Department of Economy, a large-scale, five-year experiment in hail prevention with ordinary rockets was started in the southern part of Switzerland in 1948. Its object was to ascertain whether the view frequently held in agricultural circles that it is possible to inhibit the formation of hail by ordinary hail rockets, is justified. In scientific circles, too, the undertaking of the Division of Agriculture was appreciated, because, after all, usefulness can definitely be proved only by test. The result of this five-year experiment (which, as had been agreed, was strictly limited to the type of hail rockets used in Switzerland) revealed not the slightest indication of a positive effect for these rockets, thus confirming the expectations of scientists. The final report on this experiment will be published in the near future.

Already at the outset it was found that these experiments were entirely without scientific basis. On the other hand, discussions with experts showed that the question of hail formation had received far too little attention and that it is most essential, by serious scientific research, to shed more light upon this particular field. After all, this is the only way of establishing whether there is a possibility of preventing hail or reducing its incidence. This is the reason why, in 1950, the "Swiss Federal Commission for the Study of Hail Formation and Prevention" was appointed, which began its work in the following year. This Commission operates three research stations: the first, at the Osservatorio Ticinese in Locarno-Monti, works on the question of condensation nuclei, and, besides, studies meteorological conditions. The second station, located at the Swiss Institute for Snow and Avalanche Research at Weissfluhjoch-Davos, deals with the question of the freezing nuclei, and has, in particular, started the construction of a wind tunnel for the production of artificial hail particles. The third research station, at the Federal Institute of Technology at Zürich, handles mainly the question of the physical properties of the artificial nucleation substances. On completion of the first large-scale experiment, a new operation was started last year, employing methods similar to those

applied in various countries for the modification of clouds with a view to increasing precipitation. To begin with, only ground generators for the dispersion of silver iodide were employed. This experiment, which has extended over the last two years, does not yet permit of final conclusions, which, however, is partly due to the fact that so far only a statistical evaluation of results has been possible and that we were somewhat handicapped by the scarcity of thunderstorms during the last two years.

I do not think it necessary here to point to the fact that a problematic element still attaches to the various methods hitherto employed to prevent hail. How could we expect it to be otherwise as long as we have so little knowledge of the processes involved in the formation of hail? Furthermore it is impossible to dissociate the hail problem from the whole complex of questions regarding precipitation and to treat it as an isolated problem. It is only by making a very close study of the processes generally causing precipitation, that we may hope to find a way eventually leading to a reduction in hail formation. In this connection the research programme of our Commission not only comprises the small field of hail formation but, as implied by the tasks set to our three research stations, extends more generally to the question of natural precipitation processes as such and the possibilities of influencing them.

For the continuation of research work in the field of experimental meteorology, which deals especially with the question of artificially influencing the weather processes, an international exchange of experience is of fundamental importance. As this international exchange of experience is not, to our mind, sufficiently active, our Commission has decided to organize this Symposium on experimental meteorology and to invite to Zürich persons prominent in this field from various countries. The response which our steps have found, reveals clearly how necessary such a meeting will be. It may be found in the course of our discussions that a permanent basis for discussions of this kind should be created in the shape of a loose, yet fruitful international organization.

I have the great pleasure of thanking our lecturers for having accepted our invitation and for taking upon themselves a journey to Zürich. I wish to welcome the experts from our neighbouring countries: Austria, France, Germany, and Italy, and those who came from England, Sweden, and Yugoslavia; and I am very pleased to count among our contributors and guests representatives of the meteorological circles of America, Japan, Pakistan, and Tunisia.

It is also my agreeable duty to thank the authorities, offices, and enterprises who have, by their assistance and financial support, rendered the Symposium possible. Hoping that it will prove fruitful for all concerned, I hereby declare the Symposium open.

October 4, 1954 R. Sänger, Zürich.

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(Observatoire du Puy de Dôme, Clermont-Ferrand.)

Quelques théories de l'ensemencement des nuages soumises au contrôle expérimental.

Par

H. Dessens.

Avec 6 figures.

Résumé. Aprés avoir confirmé la réalité de l'effet FINDEISEN-BERGERON, on déplore l'ignorance actuelle sur le mécanisme de création de cristaux de glace par refroidissement (neige carbonique) ou par particules solides (iodure d'argent). La désactivation des noyaux d'iodure d'argent peut être attribuée à divers facteurs: lumière, impuretés, congélation suivie d'une sublimation, condensation de vapeur à température positive; il en résulte une difficulté pour déterminer les conditions d'efficacité de l'iodure d'argent dans les nuages naturels. Dans le cas de l'ensemencement au moyen de générateurs au sol, cette efficacité n'est pour le moment certaine que sur des nuages dont la base est au-dessus de l'isotherme —4°C et le sommet au-dessous de l'isotherme —15°C.

Bien que les expériences d'ensemencement des nuages à température positive par de gros éléments (gouttes d'eau ou noyaux hygroscopiques) soient poursuivies depuis 8 ans, aucun résultat décisif n'a encore été obtenu jusqu'à ce jour; contrairement aux procédés d'ensemencement par particules glacées, celui-ci exige, pour être efficace, l'amorçage d'une réaction en chaîne dans le nuage ensemencé.

Zusammenfassung. Abb. 1 läßt die große Bedeutung erkennen, welche dem BERGERON-FINDEISEN-Effekt, zum mindesten im ersten Stadium des Wachstums der Niederschlagselemente, zukommt. Weiters wird der Verlauf einiger Experimente über die Keimbildung gezeigt; die Größen der Wolkentröpfchen wurden durch kinematographische Aufnahmen ihres Ansatzes an einem Spinnfaden gemessen. Es ergab sich, daß die häufigsten Radien 5 μ betragen und eine unerwartet geringe Streuung aufweisen.

Die Niederschlagsteilchen aus einer unterkühlten Wolke, in welcher die Keimbildung mittels Silberjodids eingeleitet worden war, zeigen Formen, die mit den von MASON, WEICKMANN, AUFM KAMPE und KELLY mitgeteilten Resultaten nicht ganz übereinstimmen; so fanden wir hexagonale Plättchen ohne Struktur bei einer Temperatur von —12°.

Der Wirkungsmechanismus von Kohlensäureschnee und Silberjodid erscheint weiterhin nur sehr ungenügend bekannt. Es werden neue Vorgänge, die zur Inaktivierung von Kernen führen, aufgezeigt: Inaktivierung als Folge einer vorhergehenden Eisbildung (SOULAGE), Inaktivierung durch Kondensation oder Anlagerung von Wasser bei positiver Temperatur (PICCA). Obwohl die Erfolge des „Impfens" im Inneren einer Wolke von —4° nicht zu bezweifeln sind, haben die Versuche zur Vermehrung des Niederschlags durch den Einsatz von zahlreichen Generatoren in größerer Entfernung von der Wolke nicht zu den erwarteten Resultaten geführt. Es wird dafür folgende Erklärung vorgeschlagen: In einer unterkühlten Wolke werden die Silberjodid-Kerne entsprechend dem FACY-Effekt aufgefangen. In der Umgebung von kondensierenden Tröpfchen entsteht ein Feld von zentripetalen Kräften durch die Wassermoleküle, welche sich gegen das Tröpfchen bewegen. Daher entstehen im Wachstumsstadium nur aus den bevorzugten Tröpfchen Kristalle und es bleibt daher ein übermäßiges Bestreuen der Wolke ohne nachteilige Wirkung, so daß man dennoch immer Niederschlag erhält.

Anderseits kann die Wirksamkeit der Keimbildung im Großen durch folgende zwei Tatsachen eingeschränkt werden:

a) Wenn die Spitze der Wolke sich über die —15°-Isotherme erhebt, kann natürliche Keimbildung eintreten.

b) Wenn die ausgestreuten Kerne eine Wolkenschicht mit höherer Temperatur passieren, bevor sie die —4°-Isotherme erreichen, erscheint es zweifelhaft, ob sie ihre Aktivität erhalten können.

Die Photographie des PIERREFITTE-Cumulus scheint diese Überlegungen zu bestätigen. Das Bild der drei Wolken zeigt eindeutig, daß die durch Keimbildung beeinflußten Wolken sich nur zwischen den Isothermen —4° und —15° entwickeln. Hygroskopische Kerne können praktisch nur wirksam werden, wenn sie eine Kettenreaktion auslösen. Ob dies tatsächlich vorkommt, erscheint noch nicht erwiesen; zu diesem Zweck wäre es am günstigsten, NaCl-Teilchen von einigen 10 μ Größe zur Keimbildung in warmen Wolken zu verwenden.

Summary. Figure 1 justifies the importance of the effect found by BERGERON and FINDEISEN, at least in the first stage of growth of precipitation elements. Some controls of nucleation experiments are then shown; the measurements of the size of cloud droplets were made by microkinematographing the capture of these droplets on a spider thread. The radii obtained for the most numerous droplets vary less than one would have expected and deviate little from 5 μ.

The precipitation particles from supercooled clouds succeeding a nucleation with silver iodide nuclei, show shapes which do not confirm all the results given by MASON, WEICKMANN, AUFM KAMPE, and KELLY; e. g. the formation of hexagonal plates without structure at about —12° could be observed.

The mechanisms of action of solid carbon dioxide and of silver iodide remain little known. New processes leading to an inactivation of nuclei have been shown: inactivation following a preceding formation of ice (SOULAGE), inactivation by condensation or fixation of water at a positive temperature (PICCA). Although the effects of seeding in the interior of clouds at a temperature below —4° are undeniable the experiments for increasing precipitation on a large scale with generators working far from the clouds have not led to the expected results. The following explanation is proposed: in a supercooled cloud the silver iodide nuclei are captured according to FACY'S effect: there is, around condensing droplets, a field of centripetal forces due to the shocks against the nucleus of water molecules moving towards the

droplet. Therefore, the privileged drops alone, at the stage of growth, give crystals and this avoids the overseeding of the cloud and always leads to precipitation.

On the other hand, the efficiency of nucleation on a large scale can be limited by the following facts:

a) If the summit of the cloud rises above the isotherm —15°, a natural nucleation may interfere.

b) If the nuclei should, before reaching the isotherm —4°, pass through a cloudy and warmer region, there is doubt that they retain their activity.

The photograph of the PIERREFITTE cumulus seems to prove these statements. The picture of the three clouds shows exactly that they certainly are affected by nucleation and would develop only between the isotherms —4° and —15°. The hygroscopic nuclei can practically be efficient only when they can initiate a chain reaction, the practical reality of which still is to be proved. NaCl particles of some tens of microns should be chosen for making nucleation in warm clouds.

Le but de cet exposé n'est pas d'établir le bilan des recherches récentes sur les précipitations naturelles ou provoquées, mais seulement de faire part de quelques réflexions à la suite d'expériences que j'ai poursuivies pendant 8 années avec l'aide de divers collaborateurs. Les références aux recherches de mon groupe seront donc relativement plus importantes que ne le sont ces recherches comparées à celles des autres groupes, et je prie les lecteurs de m'en excuser.

La réunion de Zurich a pour but d'étudier le mécanisme des précipitations et les possibilités de stimulation des précipitations ou de prévention de la grêle. Le nuage nous intéresse donc particulièrement à partir du moment où des éléments de précipitations (liquides ou solides) apparaissent parmi la multitude des gouttelettes du nuage, et jusqu'au moment où ces éléments quittent le nuage pour précipiter vers le sol.

I. Le premier stade de croissance des éléments de précipitations: condensation par effet Findeisen-Bergeron.

Face à toutes les théories relatives à l'évolution des nuages, notre attitude a toujours été systématiquement réservée. L'importance du rôle de l'effet FINDEISEN-BERGERON résiste cependant à toutes les critiques. La condensation de la vapeur d'eau sur des éléments privilégiés, avec vaporisation simultanée des gouttelettes voisines, se manifeste incidemment au cours d'expériences variées. Les 5 clichés (fig. 1) de SOULAGE [*1*] mettent en évidence, vers —12°, la croissance de cristaux de glace et l'évaporation simultanée des gouttelettes surfondues entourant ces cristaux. La croissance des gouttelettes de solutions salines aux dépens des gouttelettes d'eau pratiquement pure des nuages constitue une généralisation de l'effet FINDEISEN-BERGERON. Ce dernier mode de production des éléments de précipitation est susceptible d'intervenir dans tous les nuages de gouttelettes, indépendamment de leur température.

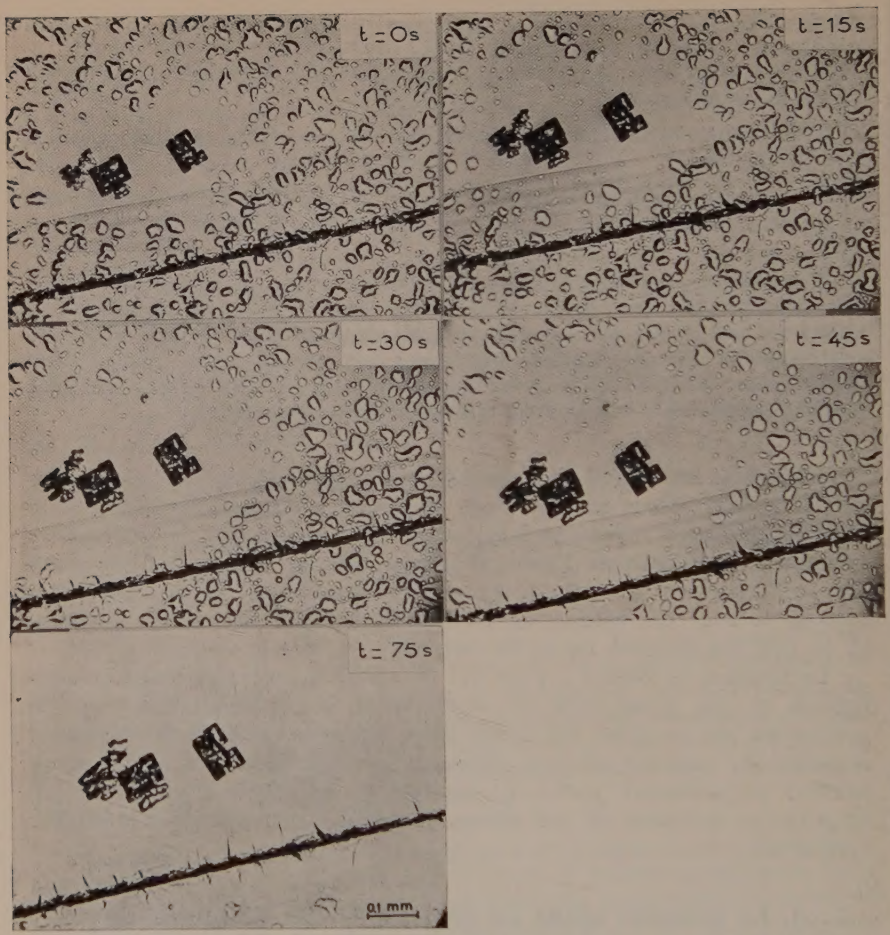

Fig. 1. Réalité du processus FINDEISEN-BERGERON. Les cristaux de glace croissent aux dépens des gouttelettes environnantes (SOULAGE).

II. Effets de l'ensemencement des nuages surfondus en particules glacées.

A. Ensemencement par refroidissement local d'un nuage surfondu.

Le refroidissement a été réalisé par introduction d'un corps froid, par détente d'un gaz ou par vaporisation d'un liquide ou d'un solide. Il n'est pas encore possible d'arbitrer les divergences de vues entre MASON [2], LANGMUIR [3] etc. concernant le mécanisme d'action d'un frigorigène tel que la neige carbonique. Ce mode d'intervention est caractérisé par l'apparition d'un grand nombre de cristaux de glace.

C'est au cours d'une telle expérience dans un stratus [4] que j'ai eu l'unique occasion de me demander si, par détente brutale et massive de liquide carbonique, il n'était pas possible d'obtenir la stabilisation d'un nuage surfondu sous forme d'un nuage de particules glacées demeurant trop petites pour que leur précipitation soit effective. Les applications de ce mode d'ensemencement se heurtent pour le moment à l'impossibilité de contrôler la concentration des particules glacées introduites dans le nuage.

B. Ensemencement par l'iodure d'argent.

1° Recherches de laboratoire.

Il est très probable que c'est bien la similitude des structures cristallines de l'iodure d'argent hexagonal et de la glace qui permet aux particules d'iodure d'engendrer des cristaux de glace. Mais le mécanisme de naissance des cristaux de glace reste indéterminé. L'absence d'expériences mettant en évidence cette naissance pour des tensions de vapeurs comprises entre les tensions de vapeur saturante de l'eau et de la glace ne permet pas de penser que les cristaux d'iodure agissent comme noyaux de sublimation. Mais d'autre part, le fait qui semble avoir été bien établi par Picca [5] que des fragments d'iodure d'argent peuvent fixer des gouttelettes d'eau à température positive puis rester dans ces gouttelettes sans provoquer leur congélation jusqu'à des températures de l'ordre de —20° laisse subsister des doutes sérieux quant au mécanisme proposé par Weickmann [6] : formation d'un film d'eau sur la particule d'iodure, congélation de ce film, et fonctionnement de la particule de glace ainsi formée comme noyau de sublimation.

Ainsi, dès l'abord, le comportement des noyaux d'iodure pose toujours un problème. De plus, l'action de ces noyaux solides est fonction de leur histoire. En dehors de la désactivation photochimique à laquelle on a attribué une importance capitale [7] [8] puis atténuée ou même nulle [9], d'autres modes de désactivation peuvent jouer un rôle essentiel. On peut actuellement se demander si des noyaux d'iodure d'argent ayant fixé par condensation de l'eau à température positive, puis refroidis à l'intérieur de ces gouttelettes, sont capables d'amorcer leur congélation vers —4°, comme cela se produit si les noyaux sont introduits directement dans des gouttelettes à cette température.

Enfin, des nombreuses expériences de Soulage [1], il résulte que certains noyaux d'iodure d'argent ayant déjà engendré un cristal de glace que l'on a laissé se sublimer sont incapables d'être actifs une deuxième fois.

2° Expériences sur le terrain.

Cet ensemble de données est insuffisant pour rendre compte du déroulement des expériences sur le terrain.

Nos essais ont le plus souvent porté sur des stratus; pour certains d'entre eux, les dimensions des gouttelettes ont pu être mesurées par microcinématographie lors de la captation sur un réseau de fils

d'araignées [*10*]: les rayons les plus fréquents ont généralement été trouvés voisins de 5 microns. Les émissions de fumées étaient réalisées soit au moyen de brûleurs du type décrit par B. VONNEGUT [*11*] utilisant une solution acétonique à 10%, soit par combustion, sur des forges portatives [*12*] ou des paniers métalliques [*4*], de charbon de bois imprégné de 2% d'iodure d'argent. Les effets observés peuvent être ainsi résumés:

L'apparition de cristaux de glace est constante si l'émission a lieu dans le sein du nuage et si la température est inférieure à —4°; ces cristaux croissent, et leur précipitation sur le sol devient habituellement sensible une dizaine de minutes après le début de l'émission de noyaux. La précipitation se fait naturellement dans la direction d'entraînement des noyaux par le vent.

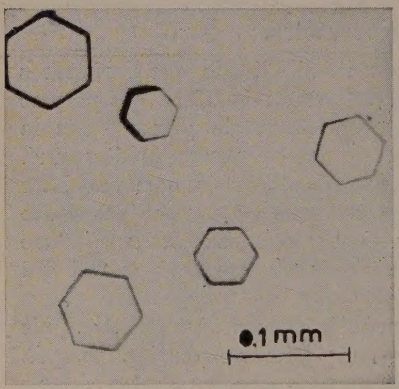

Fig. 2. Plaquettes hexagonales sans structure produites par action des noyaux d'iodure d'argent sur un stratus à —12°.

Il n'a pas été possible, après quelques dizaines d'expériences de confirmer les propositions de WEICKMANN, AUFM KAMPE et KELLY [*13*] ou de MASON [*14*] concernant la forme des cristaux (fig. 2) [*15*] [*4*].

Les effets d'un surensemencement présumé n'apparaissent jamais. D'une part il y a toujours croissance suffisante des cristaux pour assurer leur précipitation; d'autre part les cartes de précipitations qui ont pu être relevées dans de bonnes conditions [*16*] ne révèlent pas de précipitation plus faible dans les régions où l'on pouvait s'attendre, en accord avec les répartitions calculées par SERRA [*17*], à un surensemencement. Une intéressante observation de SCHAEFER [*18*] attribuant à un éventuel surensemencement une zone centrale de moindre précipitation ne se trouve donc pas confirmée. Les recherches récentes de FACY [*19*] fourniront peut-être une interprétation de cette différence de caractère entre les ensemencements par la neige carbonique (surensemencement possible) et par l'iodure d'argent (pas de surensemencement observé). Selon ce physicien, de petites particules telles que les noyaux d'iodure d'argent, sont captées par les gouttelettes en voie de condensation par suite du champ de forces centripètes régnant autour de la particule; ce champ est dû au choc contre le noyau des molécules d'eau se précipitant vers la gouttelette. Les gouttelettes en cours d'évaporation ne capteraient pas de noyaux, et les noyaux d'iodure d'argent excédentaires resteraient inutilisés ou ne seraient captés que par des cristaux en voie de croissance lorsque la tension de vapeur d'eau deviendrait insuffisante pour assurer la croissance de gouttelettes liquides.

Au cours de plusieurs expériences où les émissions étaient réalisées au-dessous de la base des nuages, des précipitations ont été observées avec

certitude: les nuages étaient alors à température négative dans leur ensemble.

La captation de gouttelettes par les cristaux induits artificiellement a été observée dans un seul cas par SOULAGE [*15*] (fig. 3) mais nous n'avons jamais eu l'occasion de soupçonner une fragmentation ultérieure de ces agglomérats.

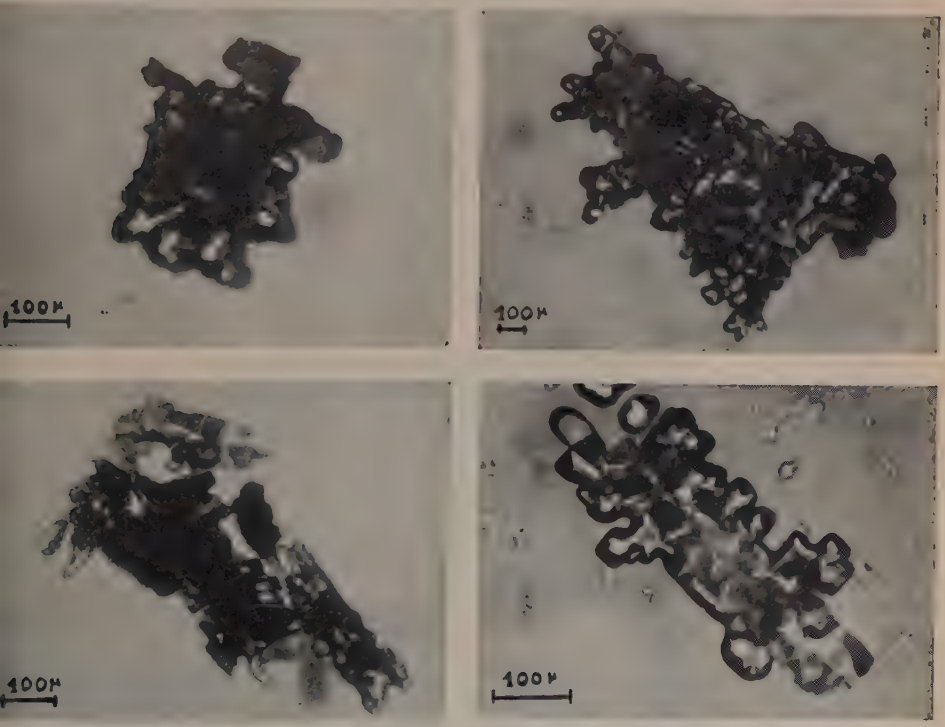

Fig. 3. Agglomérats sur des cristaux produits par Ag I dans unnuage naturel (—12°) (SOULAGE).

III. Expériences à grande échelle.

Il n'est pas question d'examiner ici les tentatives nombreuses effectuées en vue de modifier le régime des précipitations dans une région par diffusion de noyaux d'iodure d'argent à partir de générateurs au sol convenablement répartis. Je présente seulement le bilan de 3 campagnes d'émissions effectuées dans le Sud-Ouest français en vue de tenter une prévention de la grêle dans une région particulièrement exposée à ce fléau.

Supposant avec SCHAEFER [*20*], FOURNIER D'ALBE [*21*] etc. que la grêle est due à une carence momentanée en noyaux glaçogènes naturels, l'Association d'Etudes, qui a entrepris ces expériences en 1951, s'est proposé de pallier à cette carence par des émissions massives

de noyaux artificiels non seulement plus nombreux mais encore plus actifs que les noyaux naturels. Les résultats statistiques tendent, à la fin de la quatrième campagne (30 septembre 1954) à montrer que le but poursuivi a été partiellement atteint, mais nous n'exposerons pas ici ces résultats, qui ne peuvent pas être encore considérés comme décisifs. Il est sans doute plus intéressant, dans le cadre de cet exposé, d'examiner la répercussion éventuelle des émissions sur le régime des précipitations. Si l'aire et la période expérimentale (mai à septembre de chaque année) sont restées à peu près inchangées de 1951 à 1954, les techniques d'in-

Fig. 4. Ensemencements à grande échelle dans le Sud-Ouest français. Rapport à la normale des précipitations de mai à septembre 1951, 1952 et 1953. On ne peut dégager aucune conclusion après 3 années d'expériences.

sémination (générateurs VONNEGUT en 1951 et 1952, charbon brûlé sur forges en 1953, dans des paniers métalliques en 1954), le nombre des générateurs (6 en 1951, 70 en 1954) et l'intensité des émissions (moins de 10 kg d'iodure pur en 1951, plusieurs centaines de kg en 1954) ont varié dans de larges limites. On peut donc espérer qu'au cours de l'une de ces périodes de 5 mois au moins les émissions ont présenté un maximun de chances d'efficacité. Comme conséquence de l'incertitude qui règne sur la délimitation de la région pouvant être affectée par les émissions, c'est dans les relevés pluviométriques pour l'ensemble de la France que nous avons recherché si une région affectée apparaissait sur les cartes. Quelle que soit la façon dont on relève les résultats, il n'est pas possible de conclure à une modification des précipitations due aux émissions. Voici, à titre d'exemple (fig. 4), la carte des rapports du total des précipitations pour les 15 mois d'expériences de 1951, 1952 et 1953 au total normal pour les mêmes mois évalué en se référant à la période 1901—1930.

IV. Suggestions concernant l'échec relatif des expériences à grande échelle.

L'expérimentateur qui poursuit simultanément des expériences localisées dans des nuages surfondus et des expériences à grande échelle est frappé par le contraste entre les effets constants, grandioses, indiscutables obtenus dans les premières, et la difficulté de mettre en évidence les résultats des deuxièmes. Il est donc conduit à rechercher les causes de l'inefficacité au moins relative des expériences à grande échelle.

L'observation suivante incite à préciser une hypothèse: chaque fois que des précipitations ont pu être attribuées à l'intervention de noyaux d'iodure d'argent, les noyaux avaient été introduits dans un nuage à température négative; si l'émission au moyen d'un générateur au sol avait été effectuée au-dessous de la base du nuage, celle-ci était située au-dessus de l'isotherme 0°. C'est le cas du cumulus de la figure 5, qui est dans la zone d'entraînement des fumées d'un générateur situé à 20 km en amont, et qui produit, malgré ses faibles dimensions, une précipitation anormalement dense [*22*] [*23*].

Fig. 5. Précipitation très dense et très rapide d'un petit cumulus développé entre les isothermes 0° et —10° et ensemencé en noyaux d'iodure d'argent.

Rapprochant ces observations des constatations de laboratoire de Picca [*5*], on est conduit à se demander si les noyaux d'iodure qui pénètrent dans un nuage par sa base à température positive sont susceptibles d'agir lorsqu'ils parviennent à l'isotherme —5°. Dans le

cas d'une introduction directe dans la région surfondue, il est possible que les noyaux agissent après captation par les gouttelettes en cours de condensation, selon le processus décrit par FACY [*19*]. Le noyau provoquerait alors la congélation de la gouttelette comme cela se produit lorsqu'on fait pénétrer dans une gouttelette surfondue un fil d'araignée pollué de noyaux d'iodure d'argent [*24*]. Par contre, le passage dans une région nuageuse à température positive détruirait l'efficacité du noyau, par un processus encore inconnu (une condensation liquide superficielle peut-être), et la plupart des expériences à grande échelle, réalisées avec des bases nuageuses à température positive, ne pourraient être suivies d'aucune modification des nuages ou des précipitations.

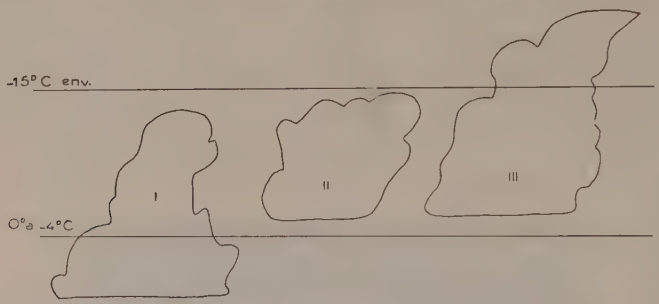

Fig. 6. Possibilité d'efficacité des noyaux d'iodure d'argent en fonction de la situation du nuage.
I. Innefficacité possible des noyaux après passage dans la couche nuageuse à température positive.
II. Type de nuage soumis à une pleine action des noyaux d'iodure d'argent.
III. Ensemencement naturel en particules glacées formées au-dessus de l'isotherme —15°.

On sait d'autre part que, si parfois la congélation massive d'un nuage n'apparaît qu'au voisinage de l'isotherme —40°, généralement des particules glacées en nombre appréciable apparaissent dès que la température s'abaisse au-dessous d'une valeur située vers —15°. L'observation des résidus congelés de certaines «tours» de cumulus permet d'être affirmatif à ce sujet [*25*]. Les nuages qui seraient modifiés par une insémination à partir du sol seraient donc exclusivement ceux dont la base est située au-dessus de l'isotherme 0° (ou peut-être —4°) et dont le sommet n'atteint pas l'isotherme —15° (fig. 6). Cette hypothèse, encore bien fragile, expliquerait l'échec relatif des expériences à grande échelle et limiterait le champ d'utilisation des ensemencements par l'iodure d'argent.

V. Tentatives de modification des nuages à température positive.

Elles sont fondées sur la captation des gouttelettes de nuage par de gros éléments: grosses gouttes d'eau pure ou gouttes de solution condensées sur de gros noyaux hygroscopiques. Une différence essentielle avec les méthodes précédentes tient au nombre restreint des éléments

qu'elles mettent en jeu [*22*]. On ne peut espérer obtenir des précipitations appréciables que par déclenchement de la réaction en chaîne décrite par Langmuir [*26*]. Or, si le mécanisme de cette réaction paraît très vraisemblable, nous n'avons pas encore de preuves suffisantes de son importance dans la production des précipitations.

Le nuage contenant de l'eau en abondance, on ne comprend pas pourquoi certains expérimentateurs [*27*] ont, après Langmuir, introduit les gros éléments sous forme de gouttes d'eau pure, alors qu'il est beaucoup plus commode d'apporter dans la région choisie du nuage des noyaux salins calibrés à la dimension voulue. Après avoir isolé et étudié les noyaux de condensation de l'air [*28*], j'ai indiqué dès 1948 [*29*] pourquoi j'avais choisi le chlorure de sodium pour ces essais et pourquoi les particules utilisées devaient avoir un rayon supérieur au micron, c'est-à-dire être comparables aux plus gros noyaux naturels que j'avais précédemment isolés dans l'atmosphère [*30*]. Mes expériences se poursuivent avec continuité depuis cette époque, et des résultats ont été publiés en 1950 [*31*]. Au cours des années suivantes, l'incertitude quant à l'efficacité des inséminations par gros noyaux salins a subsisté. Ni les publications récentes de Bowen [*27*] ni celles de Schaefer [*18*] ou de divers autres auteurs ne nous semblent de nature à lever cette incertitude. Peut-être Fournier d'Albe nous apportera-t-il enfin, à la suite d'efforts judicieux basés sur de sérieuses études préliminaires [*32*], des preuves décisives.

VI. Conclusion.

Si je me suis hasardé à introduire une hypothèse mal assurée au sujet du comportement des noyaux d'iodure d'argent, c'est pour insister sur nos hésitations en ce qui concerne ce comportement. Entre les possibles désactivations par la lumière, par les impuretés, par l'eau ou la vapeur, par une congélation suivie d'une sublimation, on a le choix pour expliquer l'échec éventuel de toute expérience. Il est urgent de préciser les propriétés glaçogènes des noyaux d'iodure, et leurs modifications sous l'action de divers facteurs. On jugera ensuite s'il y a lieu de rechercher d'autres particules, si toutefois ces désactivations ne constituent pas une propriété commune à tous les noyaux glaçogènes, comme Soulage peut déjà le suggérer.

Réussira-t-on avec les gros noyaux hygroscopiques des expériences aussi décisives que celles qui ont été réalisées avec les particules d'iodure d'argent? Dans quel sens les efforts doivent-ils se concentrer? La réunion de Zurich doit, après une confrontation des idées sur ces sujets, nous guider vers les voies à suivre.

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The Physics of Natural Precipitation Processes.

By

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With 11 Figures.

Summary. A critical survey is given of the physical processes responsible for the release of precipitation such as drizzle, rain, snow, and hail in middle and low latitudes. By suitable analyses of long series of airplane observations of characteristic states in layer and shower clouds indications are derived for the type of the efficient physical processes. Investigations carried out at the Imperial College during the last years are discussed in a brief report: studies on the growth of precipitation elements in cloud models and theoretical conditions for the formation of showers are compared with both visual and radar observations.

Zusammenfassung. Die physikalischen Vorgänge, welche für die Auslösung von Nieseln, Regen, Schnee und Hagel in mittleren und niedrigen Breiten der Erde in Frage kommen, werden einer zusammenfassenden Prüfung unterzogen. Mit Hilfe geeigneter Analysen langer Serien von Flugzeugbeobachtungen der charakteristischen Zustände in Schicht- und in Schauerwolken werden Hinweise auf die Art der wirksamen physikalischen Prozesse abgeleitet. In einem kurzen Bericht werden die in den letzten Jahren am Imperial College durchgeführten Arbeiten besprochen: Studien über das Wachstum der Niederschlagselemente in Modell-Wolken und die theoretischen Bedingungen für die Entstehung von Schauern werden mit visuellen und Radar-Beobachtungen verglichen.

Résumé. Etude critique des processus physiques responsables de la formation de la bruine, de la pluie, de la neige et de la grêle aux latitudes moyennes et basses. Des analyses de longues séries d'observations faites en avion des états caractéristiques au sein de nuages strafiés ou cumuliformes permettent de donner des indications sur la nature des phénomènes physiques déterminants. Court aperçu de travaux récents effectués à l'Imperial College: des recherches sur la croissance des germes de précipitations dans les nuages de laboratoire et les bases théoriques de la formation des averses sont comparées aux observations visuelles et par radar.

I. Introduction.

A non-precipitating water cloud is composed of minute droplets of order 10 μ in diameter possessing terminal velocities of only a few cm./sec. Thus considerable growth of a cloud particle must occur before it can gain

a falling-speed sufficient for it to fall out of the parent cloud, survive evaporation in the unsaturated air beneath, and reach the ground as a precipitation element. The various mechanisms by which precipitation elements may be formed are the main theme of this paper.

II. Forms of Precipitation.

The size of precipitation elements is determined to some extent by the strength of the updraught producing the cloud and by the humidity in the subcloud layer. Widespread layer clouds are associated with upcurrents usually less than 0.5 m./sec., so that droplets with radii approaching 80 μ can fall out of them and approach the ground. The distance which a drop can fall through unsaturated air before completely evaporating is roughly proportional to the fourth power of the initial radius. In an atmosphere of 90% relative humidity the distances for various initial radii are, according to FINDEISEN (1939),

Radius	*Distance fallen*
10 μ	3.3 cm.
100 μ	150 m.
1 mm.	42 km.

Since the bases of dense clouds generally lie at least a few hundred metres above the ground, a value for the radius of about 100 μ may be regarded as a lower limit to the size of precipitation elements.

Precipitation composed entirely of drops little larger than this commonly falls in damp weather from low, shallow, layer clouds and is called *drizzle*. *Rain*, consisting of larger drops having radii up to about 2 mm., is produced by layer clouds some thousands of metres deep such as are associated with fronts and depressions. The heaviest rains composed of relatively large drops fall from cumulus clouds whose depth may reach 10 km., and which contain powerful upcurrents of several m. sec. Precipitation from these clouds is sporadic, for their horizontal extent is only a few kilometres and the active life of individuals is less than one hour. These rains are described as *showers*.

Shower clouds which extend well above the 0° C isotherm are believed to contain ice particles, mainly in the form of graupel or hail, in their upper regions, but these may often melt before reaching the ground. However, very deep, vigorous clouds may produce very large hailstones which, in hot climates, are occasionally as large as oranges. In cold weather the precipitation may reach the ground entirely as graupel or small hail.

Even the largest snowflakes have fall-speeds hardly exceeding 1 m./sec. and so *snow* falls only from stratiform clouds and from weak or decaying convective clouds which contain small vertical air currents.

III. Physical Processes Responsible for Precipitation Release.

Unless the concentration of could particles is extremely small it is impossible to produce precipitation by continued condensation of vapour

on the cloud droplets. In general the concentrations of nuclei are such that supersaturations greater than 0.1% are unlikely to be exceeded in layer clouds; although under these conditions a droplet may grow by condensation to a radius of 10 μ in a few minutes, it would take many hours to grow to radius 100 μ. In such a long period the droplet will have fallen out of the cloud before reaching a size at which it could survive evaporation in the drier air beneath. In the case of a shower cloud, the times required would greatly exceed the life of the cloud.

The search for an adequate physical explanation of the formation of precipitation elements was apparently concluded with the publication of a classical paper by BERGERON (1935) in which he stated that the only factor which could account for the release of precipitation was the appearance of a few ice crystals among a much larger population of supercooled droplets in those parts of the cloud where the temperature was below —10° C. In such *mixed clouds* the state of water-saturation represents a supersaturation with respect to ice of 10% at —10° C, and 21% at —20° C, so that rapid growth of the ice crystals would be expected. The physical mechanism discussed by BERGERON was just that put forward earlier by WEGENER (1911), i. e. "The vapour pressure will adjust itself to a value between the saturation values over ice and over water. The effect of this must then be, that condensation will take place continually on the ice, whereas at the same time liquid water evaporates (from the droplets), and this process must go on until the liquid phase is entirely consumed."

BERGERON postulated that almost every raindrop (diameter > 0.5 mm.) originates as an ice particle which 'grows copiously' in this way. and therefore that all rainclouds must extend well above the 0° C level. The WEGENER-BERGERON hypothesis received strong support from FINDEISEN (1939) who, on the basis of aerological observations made over Germany, stated categorically that all rain composed of large drops originates as snow or hail. Further data on the temperatures of cloud summits described in the next section appeared to support this thesis, so that the BERGERON hypothesis came to be generally accepted during the following decade; in the absence of detailed quantitative arguments, all other possible processes were deemed to be much too slow.

However, it must have been obvious to both meteorologists and aviators that in tropical regions showers often fell from clouds whose tops did not reach within some kilometres of the 0° C level. Rumours to this effect were current from time to time, but for some peculiar reason very few reports of detailed observations were published and the views of the European meteorologists were not seriously challenged. Not that the possibility of the larger droplets in a wholly water cloud might continue to grow by collision with their smaller neighbours was entirely dismissed. Indeed (FINDEISEN 1939), calculated the radii with which droplets of initial radius 30 μ would be expected to fall from a layer cloud of liquid-water content 1.25 g/m^3 and found values of 100 μ, 200 μ and 400 μ for cloud thicknesses of 150 m., 400 m., and 1000 m. respectively. However, he rejected this result as contrary to experience, and believed his theory to

be in error in that it assumed that a larger falling drop collects all the droplets in its path, none being swept aside. He was firmly of the opinion that this coalescence mechanism was a slow and inefficient method of precipitation release capable of causing only falls of drizzle.

But, in recent years, careful visual and radar observations have accumulated which show beyond all doubt that, in tropical regions, heavy rain falls from clouds which are entirely beneath the level of the 0° C isotherm. In these regions this level may be above 5 km. whereas in temperate latitudes it is often below 2 km., and here equally deep clouds commonly reach heights where the temperature is below —20° C so that their tops would almost certainly contain ice crystals. It does not follow, however, that their presence is *essential* to the production of rain, as we shall see later.

A more detailed evaluation of droplet growth by coalescence in wholly water clouds was made possible by the publication of a paper by LANGMUIR (1948) in which he calculated the efficiency with which a drop of given size would collect smaller droplets lying in its fall path. He went on to calculate the growth of large water droplets by this coalescence process following their introduction into the upper parts of convective clouds. More detailed treatments by BOWEN (1950) and LUDLAM (1951) start from the assumption of the presence, near the cloud base, of a few particles larger than the main population of cloud droplets and of the occurrence of a significant updraught throughout a considerable depth of cloud. BOWEN, who has assumed these larger drops to arise by chance collisions of droplets in the lower parts of the cloud, has calculated their subsequent growth by condensation and coalescence in clouds of constant updraught and constant liquid-water content. He demonstrates that the process may reasonably result in the production of raindrops in clouds several thousand feet deep and describes observations which indicate that in Australia showers frequently develop by this process.

The suggestion was originally made by WOODCOCK (1950) that the larger droplets required to initiate the coalescence mechanism might be supplied by the giant salt nuclei found by him in concentrations of order 1/litre in the sub-cloud layer over the sea, and which originate as spray droplets of radius 20—30 μ.

A larger droplet, whatever its origin, will be carried up in the ascending air, but will be falling relative to the ordinary cloud droplets and so will collide and (presumably) coalesce with them. The drop thus grows at an ever-increasing rate and, ultimately, if the updraught extends to a sufficient height, its rate of fall will exceed the speed of the updraught and the drop will return to the cloud base, growing as it descends. Detailed calculations indicate that this process could produce raindrops from convective clouds a few km. deep and sustained by updraughts of a few metres per sec. In temperate regions this will usually mean that the top of the cloud will extend above the 0° C level and so may contain ice crystals. It may therefore be a difficult matter to decide which of the two possible mechanisms is responsible for the initial release of precipitation, since both may be active

Once an ice crystal growing in a dense supercooled cloud has become appreciably larger than a cloud droplet its growth will be greatly accelerated by accretion of these droplets which will freeze on impact to form ice pellets of irregular shape. It can be shown that in vigorous convective clouds, the BERGERON sublimation process is generally only of importance in the early stages of development of a precipitation element.

The growth of drops by coalescence in layer clouds containing updraughts of only a few cm./sec. has been investigated by MASON (1952). He shows that because these clouds generally exist for much longer than shower clouds, the larger droplets necessary to initiate coalescence may develop *in situ* by condensation, but that they cannot grow much larger than drizzle-size unless water contents considerably larger than those usually measured are assumed. Thus it appears that the rain which falls from the thick layer-cloud systems of extra-tropical regions is probably initiated almost entirely by the growth of ice crystals which, however, must aggregate to form snowflakes if they are to produce raindrops of the observed size. The predominance of the BERGERON process in precipitating layer clouds is borne out by radar studies which often reveal the presence of a strong band of echo (the melting band) just below the 0^0 C level, this being associated with the melting of snowflakes. Radar can be used to provide statistics on the frequency of rainfall associated with the process since the presence of the melting band implies the absence of updraughts stronger than 1 m./sec. necessary for the production of rain by the coalescence process.

Having given a brief, general account of the main processes which may be responsible for the release of precipitation, and before discussing the results of detailed calculations, it seems appropriate to review the more important observational evidence which may throw some light on the physical processes at work.

IV. Observational Data on the Characteristics of Precipitating Clouds.

Three parameters which will obviously have an important bearing on which particular mechanism is likely to be dominant in the release of precipitation from a particular cloud or cloud system are the temperature of the cloud base, the cloud thickness, and, most important, the temperature of the cloud summit. The base temperature will largely control the liquid-water content of the cloud which, together with the cloud thickness will largely determine whether or not raindrops may be produced by coalescence, while the cloud-summit temperature will indicate the likely presence or absence of ice crystals. These three parameters can be readily measured from an aircraft fitted with a suitable thermometer and an altimeter and, in the case of cumulus clouds in the general vicinity of a radio-sonde ascent, from theodolite readings taken on the ground. Unfortunately, reliable observational data of this kind are rather scanty but those which are available will now be summarised.

A. Observations on clouds in middle latitudes.

An analysis of the precipitating clouds reported during daily weather flights made from Königsberg during 1935—7 was made by MANN (1940) which showed that on those occasions when rain resulted from melting snowflakes the average cloud-summit temperature was —13.5° C. On the other hand, the tops of clouds producing drizzle or intermittent light rain were, in many cases, only a degree or two below 0° C. An increase in intensity of precipitation of a particular type was, in general, associated with higher cloud-base temperatures.

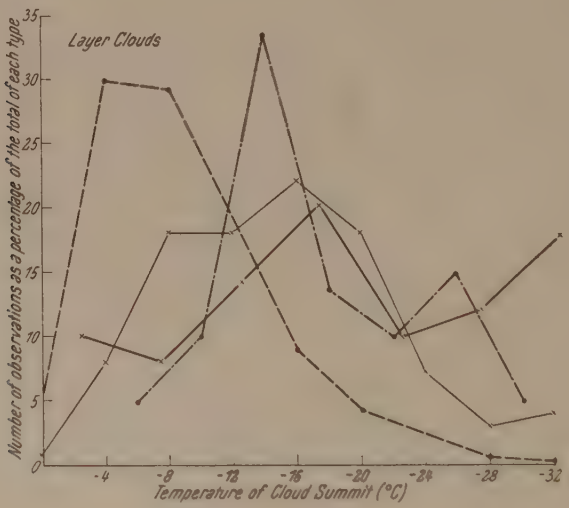

Fig. 1. The cloud-summit temperature of layer clouds as deduced from aircraft soundings.

— — — — — — PEPPLER, supercooled waterclouds, 774 cases.
—·—·—·—·— PEPPLER, non-precipitating clouds containing snow crystals, 81 cases.
———————— PEPPLER, precipitating clouds, 138 cases.
———————— MASON and HOWORTH, precipitating clouds, 52 cases.

The most extensive observations on the characteristics of layer clouds are those of PEPPLER (1940a) based on the reports of over 9000 aircraft flights made over Germany. The frequency distribution of cloud-top temperatures for (a) supercooled water clouds with no detectable ice crystals, (b) clouds containing snow crystals, (c) clouds producing rain or snow, (d) clouds producing drizzle, are shown in Figs. 1 and 2, the essential statistics being summarised in Table 1. The results of a similar analysis carried out by MASON and HOWORTH (1952) for clouds over N. Ireland are also included. Of the clouds analysed by PEPPLER in which ice particles were detected, 20% were warmer than —12° C, nearly 50% warmer than —16° C and 70% warmer than —20° C. This, together with the fact that of the supercooled clouds containing *no* crystals, about 30% were colder

than —12° C, only 12% colder than —16° C and only 5% colder than —20° C, suggest that, on average, a sharp rise in the production of ice crystals occurs in the temperature range —12° C to —16° C.

Apart from the abundance of ice crystals, the probability of the development of precipitation will depend on the cloud thickness, the height and temperature of the cloud base. The position of the cloud base relative to the 0°C isotherm will determine the depth of cloud in which aggregation of snow crystals to form precipitation elements may occur. The analyses of Peppler and of Mason and Howorth suggest that aggregation of crystals may not readily occur at temperatures much below —5°C.

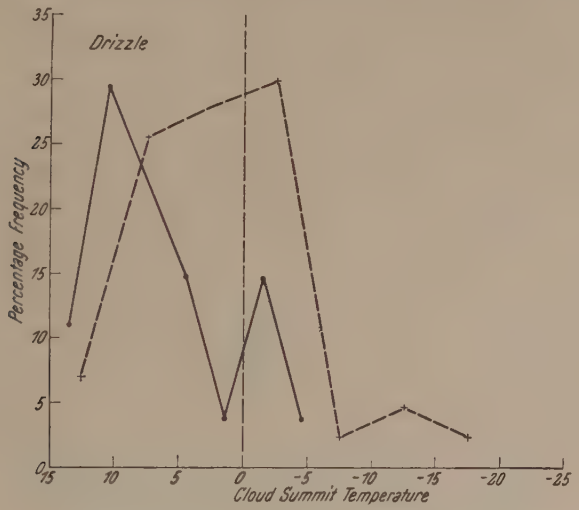

Fig. 2. The summit temperatures of layer clouds producing drizzle.
——————— Peppler, 27 cases.
— — — — — — Mason and Howorth, 45 cases.

We turn now to the observations which have been made on shower clouds in middle latitudes. Peppler (1940b) has analysed 223 flights made into cumulus clouds which precipitated at some stage over Germany. On 75% of the 79 occasions during which precipitation was encountered during the sounding the minimum temperature measured was below —12°C and there were *no* cases of rain falling from clouds wholly below the 0°C level. The 32 cases in which the cloud summits were actually reached are analysed in Table 1 and Fig. 3. That showers falling over the sea tend to be associated with appreciably warmer clouds than is the case over land was intimated by Findeisen (1942) and clearly emerges from the work of Schwerdtfeger (1948) who analyses the soundings made on 250 occasions over the sea near 60°N 13° W when showers were observed and the cloud summit temperature was determined.

Table 1. *Characteristics of Clouds in Middle Latitudes.*

Author	Cloud Type	Cloud Summit Temperature					Base Temp		Cloud Depth (z)	Remarks
		$>0°C$	$>-5°C$	$>-12°C$	$>-20°C$	Max. Frequency	$>0°C$	$>-5°C$		
PEPPLER (1940)	Supercooled water clouds			70%	95%	−4/−8°C	36%	74%		
	Non-precipitating layer clouds containing snow crystals			15%	> 60%	−12/−16°C		70%	73% with z = 1—4 km.	Icing encountered on only 22% of occasions with $T < -8°C$ but on 63% of occs. with $T > -4°C$
	Layer clouds giving rain/snow		9% warmer than −6°C	36%	75%	−8/−20°C	70%	90%	70% with z = 1—4 km.	Icing on only 15% of occs. with $T < -8°C$, but on 64% of occs. with $T > -4°C$
	Drizzle-producing clouds	82%	100%						mostly < 2 km.	
MASON & HOWORTH (1952)	Layer clouds giving rain/snow	4%	8%	28%	55%				No precipn. from clouds with z < 500m. Cont. rain only if z > 2¼ km	Only 1 case of cont. rain from non-supercooled cloud. Snow clouds always colder than −12°C
	Drizzle-producing clouds	58%	87%							
PEPPLER (1940b)	Shower clouds	0	0	0	44%	Mean temp −21°C	90%			Av. base temp. +7°C
	Non-precipitating cumulus			99%						Av. base temp. +2°C
SCHWERDTFEGER (1948)	Showers over the sea	8% 20%		45% 64%	all showers, summer showers	−13°C −3°C				
BRAHAM et al (1951)	Summer Cu giving radar echoes in New Mexico	0	0	0	< 20%	−12/−36°C	Av. ≃ 10°C			

Again the results are shown in Fig. 3 and Table 1. The peak of the frequency-distribution curve at —3°C is due very largely to the summer cumulus, while that at —13°C results mainly from observations made during AUTUMN and WINTER when non-freezing showers were observed only very rarely. These statistics suggest that showers may be produced by the coalescence process in the maritime cumulus of middle latitudes, particularly in the summer when the cloud-base temperatures are relatively high.

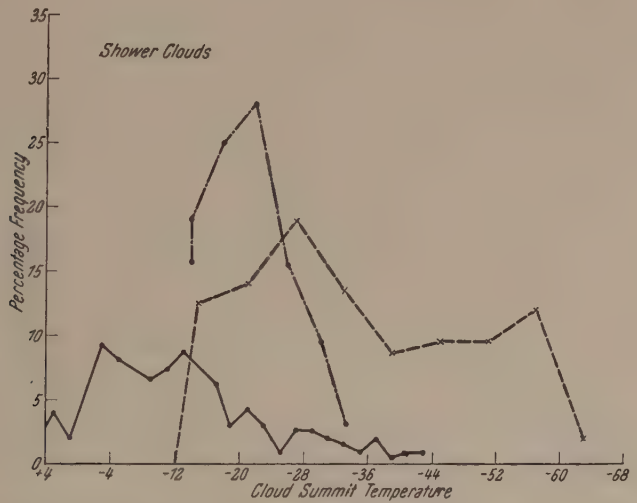

Fig. 3. The summit temperatures of shower-producing clouds over land (BRAHAM et al., PEPPLER) and over the sea (SCHWERDTFEGER).
———————— SCHWERDTFEGER, 250 cases.
— — — — — — BRAHAM et al., 127 cases.
—·—·—·—·— PEPPLER, 32 cases.

Recently, BRAHAM, REYNOLDS and HARRELL (1951) have observed summer cumulus in New Mexico by double theodolites and radar, and found that radar echoes never developed when the minimum summit-level temperature was higher than —12°C. At temperatures between —12°C and —24°C only about one-fifth of the clouds produced echoes and a few clouds gave no echoes even at temperatures below —30°C. The results of these authors show a similar trend to the other curves of Fig. 3, although having a displacement which suggests that shower formation occurs less readily in New Mexico than over Europe. Of the non-precipitating cumulus studied in New Mexico, 75% were colder than —12°C in striking contrast to a figure of only 1% for those forming over Germany. This implies that, on average, the concentrations of ice nuclei at cloud level over New Mexico may be much lower than over Europe, but other factors such as differences in the liquid-water content of the clouds and the environmental conditions may be responsible for their differences of behaviour.

Radar studies carried out in Sydney, Australia, by BOWEN and his colleagues have clearly shown that rain may be released by either the ice crystal process or by coalescence in this warm temperate region. DAY (1953) has classified the radar echoes observed throughout 1950 into 3 categories; those showing melting bands indicative of the BERGERON process (30 cases), non-freezing showers (17 cases) and complex echoes such as are produced by cold-frontal showers, and ill-defined cloud systems (24 cases). The Australian group have also used radar-equipped aircraft to examine precipitating clouds and they have published a number of case histories of showers falling from non-supercooled clouds. In all of the cases reported the cloud-base temperature was above 10°C, the cloud thickness more than 5000 feet and the clouds were located either over the sea or near the coast where large salt nuclei were probably present in sufficient quantities to start the coalescence process.

The statistics on summit temperatures of cumulonimbus occurring over land suggest that there the coalescence process is much less effective. But, the fact that the cloud top extends well above the 0°C isotherm does not mean necessarily that the shower was not *initiated* by the coalescence of drops or that the presence of ice crystals was essential for the release of precipitation. Indeed, BATTAN (1953) who has analysed the radar records of the Thundstorm Projecter obtained in Ohio in the summer of 1947, finds that although the visual cloud tops invariably reached the —20°C level and often a great deal higher, in about 60% of the 123 cases, the whole of the *initial* radar echo was located at temperatures above 0°C. The mean temperature of the first echo top was +0.4°C and that of the echo base, +10°C.

B. Observations on clouds in tropical and sub-tropical latitudes.

There is still a paucity of well-documented information on the characteristics of the clouds which produce precipitation in low latitudes, but during the last few years observations have slowly accumulated which show that heavy rain may fall from clouds which are entirely below the 0°C level, while theoretical calculations indicate that conditions in the tropics may be more favourable for the coalescence process than elsewhere. There is therefore good reason to believe that drop growth by coalescence may be the predominant mechanism for releasing showers from tropical clouds. Published case histories of rain from non-supercooled tropical clouds are summarised in Table 2. In addition, VIRGO (1950) has analysed the reports of the heights of cloud tops made by pilots flying the triangle Trinidad-Barbados-Grenada which reveal that on 75% of the days in 1946 the clouds did not reach the 0°C level, and yet Barbados had 184 days with rain. Trinidad 236 days and Grenada 210 days. MORDY and EBER (1954) from a recent study of trade-wind cumuli in Hawaii found that rain generally occurred when the clouds were 5000 ft or more in depth. The lowest cloud-summit temperature was +7°C, the 0°C level always being above 14,000 ft.

Table 2. *Reports of Rain from Non-Supercooled Tropical Clouds.*

Author	Location	Cloud Base (ft)	Cloud Thickness	Base Tamp (°C)	Summit Temp (°C)	Remarks
HEYWOOD (1940)	Hong Kong	1000	7000	23	13.5	Ns. giving 3.2 mm rain at ground
KOTSCH (1947)	Guam	1000	4500		17.5	Ns. giving moderate rain 0° C isotherm at 17,300 feet.
HUNT (1949)	Seychelles	1200—1500	7000—10,000		11—12	Cb. giving moderate to heavy showers
DAVIES (1950)	East Africa	Few hundred feet	10,000	24	5	

Also quotes 3 other cases of showers falling from Cb with tops at 12,000 ft., 6000 ft and 8000 ft. respectively, where temperatures were still well above 0° C.

V. The Growth of Precipitation Elements in Layer Clouds.

We have seen that the observational evidence, particularly that provided by radar, indicates very strongly that the WEGENER-BERGERON process is mainly responsible for the release of precipitation from stratiform clouds, the coalescence mechanism giving rise to only drizzle or very light rain.

The most detailed calculations on the growth of ice crystals in a layer cloud have been made by WEXLER (1952) with the object of computing the variation of radar-echo intensity with height above the melting level. The crystals were assumed to originate 3 km above the 0°C level and to grow in a constant updraught of 10 cm/sec. as hexagonal plates of constant thickness. If they were assumed to grow solely by diffusion in a water-saturated atmosphere their computed masses on arriving at the 0°C level were much larger than those normally observed for single crystals, and also the computed radar-echo intensity increased with decreasing height much more rapidly than is observed. WEXLER therefore concluded that, in layer clouds with small updraughts, water droplets are not abundant and that the ice crystals do *not* grow at water saturation but at a humidity intermediate between water- and ice-saturation. By assuming that all the water created by the updraught within each height interval is deposited on the growing crystals within that region, so that there is no storage of water in the form of droplets, he was able to obtain much better agreement between computed and observed values of the radar-echo intensity as a function of height. But, the results which emerge from such calculations depend a good deal on the assumptions made concerning the geometry of the growing crystals and whether or not one assumes a steady-state to prevail. That nimbostratus giving

continuous precipitation probably does not contain appreciable concentrations of supercooled droplets is strongly indicated by PEPPLER's observations that icing was only rarely encountered at temperatures below —8°C but was experienced on more than 60% of occasions when flying between the 0°C and —4°C levels.

There is some visual and radar evidence that aggregation of snow crystals generally occurs *above* the 0°C level but this process is almost certainly greatly accelerated in the melting zone which may be only 150m deep. It has been recently shown by MASON (1955) that the intensity of the radar melting band relative to the echoes from above and below can be interpreted only if one assumes one snowflake to aggregate, on average, with two or more others in the melting zone. The variation of radarecho intensity with height in steady precipitation can now be interpreted quantitatively in terms of the growth, aggregation and melting of snow crystals.

We can now estimate the concentrations of snow crystals which must exist above the 0°C levels in that region of the cloud where aggregation will rarely occur. For precipitation composed of plane dendritic crystals of diameter 3.5 mm., mass 0.5 mg., and fall speed 50 cm/sec., falling at a rate of 3 mm/hr., the required crystal concentration is about 30/litre. If these crystals were formed by freezing nuclei carried up through the cloud base, the necessary concentration of nuclei (assuming one to be required for each crystal) would be greater in the ratio of the terminal velocity of the crystals to the speed of the updraught — say, by 5 to 1. This suggests a nucleus concentration of 150/litre, which according to measurements made by various workers, rarely appears at temperatures above —20°C or —25°C. However, the observations described above suggest that rain probably formed by the BERGERON process frequently falls from clouds with summit temperatures above —15°C.

This apparent deficiency of efficient ice-forming nuclei may perhaps be made good by the fracture of the large dendritic snow crystals during collision, and by frictional drag with the air when small ice splinters may become torn off to serve as nuclei for the growth of new crystals. It appears possible that this process together with the production of small ice particles during the freezing of drops which has been recently observed in the author's laboratory, could multiply the numbers of original nuclei by the 2 or 3 orders of magnitude necessary to explain why layer clouds tend to precipitate when their tops become colder than about —12°C. It is perhaps not a coincidence that PEPPLER's cloud observations indicated a sharp increase in the rate of production of ice crystals in the temperature range —12°C to —16°C, since it is just in this range that the growth of large dendritic crystals is favoured.

Very careful observations are required to establish the temperatures at which the growth of precipitation elements may start inside the cloud and to exclude the possibility of the layer being seeded naturally from above; the use of millimetre radar may prove a powerful tool in this connection.

The growth of water drops by coalescence in layer clouds has been considered in some detail by MASON (1952). He suggests that the growth periods of cloud droplets are limited by the fact that they are continually being transferred by eddies between the interior and the boundaries of the cloud and shows that a very few may remain inside the cloud for a time much longer than average and grow to a radius of about 20 μ by condensation, at which size they are capable of growing by coalescence. Calculations are made of the rate at which droplets originating on salt nuclei of given mass grow by both condensation and coalescence with smaller droplets in layer clouds of given uniform updraught, mean temperature, supersaturation and liquid-water content (see Fig. 4). It is shown

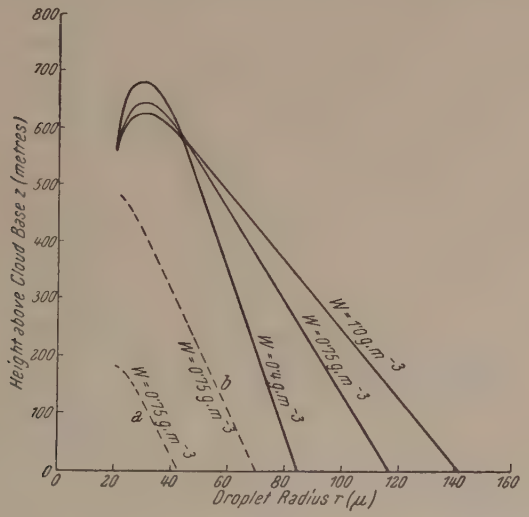

Fig. 4. Radius of droplet as function of its height above cloud base for different liquid-water contents W. The effect of varying the nuclear mass, the speed of updraught and the supersaturation on the droplet trajectories. Full curves: nuclear mass = 10^{-13} g; T = 273° K; supersaturation = 0.05 per cent; U = 10 cm/sec. Pecked curves: nuclear mass = 10^{-13} g; T = 273° K; supersaturation a = 0.05 percent, b = 0.025 percent; U = 5 cm/sec^{-1}. (Reproduced by courtesy of the Royal Meteorological Society.)

that clouds sustained by updraughts of up to 10 cm/sec. with no turbulent motion would be incapable of producing drizzle at the ground unless their liquid-water contents were considerably higher than measured values indicate. It is therefore suggested that turbulence plays an important part in releasing precipitation from thin non-supercooled layer clouds by increasing the effective fall-path of some larger drops among their smaller neighbours; this would lead increased growth by coalescence. The time-scale of the process is important; it turns out that if the larger droplets necessary to initiate coalescence are to develop *in situ* in the cloud, the latter must exist for 3 or 4 hours before producing drizzle.

VI. The Release of Precipitation from Shower Clouds.

Precipitation from shower clouds is generally of greater intensity and shorter duration than from layer clouds, the elements being generally of larger mass. The greater vertical depth of the clouds, their stronger updraughts and higher concentrations of liquid water all ensure rapid growth of the precipitation elements by an accretion process.

Cumulus clouds appear to consist of a large assemblage of rising bubbles of buoyant air having characteristic diameters of about a kilometre. SCORER and LUDLAM (1953) suppose that each rising bubble has an extensive wake into which wastes and mixes with the surrounding drier air (this process will be greatly accelerated when the bubble reaches the cloud periphery), and that a big cloud is largely composed of these wakes and the remains of earlier bubbles, with the cores of active bubbles forming localised regions of high liquid-water content and strong vertical upcurrents as suggested in Fig. 5. Although a big cloud may be recognised for an hour or more, the life of an individual bubble may be restricted to only a few minutes.

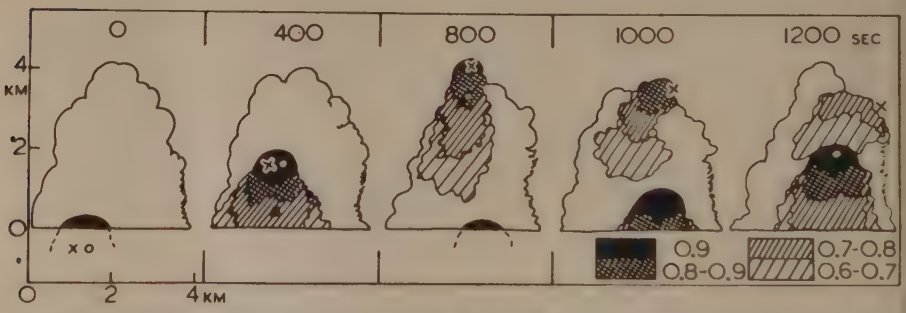

Fig. 5. Schematic representation of the structure of cumulus. The approximation of the liquid-water content to that in air rising from the base unmixed is indicated for two successive rising bubbles of cloud air. The successive positions of two cloud particles, one of which grows into a precipitation element, are also shown.

In considering the *onset* of precipitation in large cumulus clouds it can be assumed that the first precipitation elements are grown in the bubble cores which rise without mixing from the cloud base to near its top. (Recent measurements indicate that liquid-water contents very close to the theoretical adiabatic maximum values are encountered in localised regions inside large cumulus.) This means that we assume the most favourable conditions for shower formation and that the effect of any dilution of the cloudy air must be to increase our subsequent estimate of the size of a cloud which is capable of producing a shower. In order to become a precipitation element (raindrop or ice pellet) a particle must reach some rather critical size during the time taken for cloud air to rise from the base to the summits, such that it shall have settled

some hundreds of metres relative to the air, gained a fall-speed about equal to that of the updraughts near the cloud top ($\simeq$ 1 m/sec.), and have the capacity for falling with insignificant shrinking through several hundred metres of unsaturated air — and hence the opportunity to survive even if caught in the general evaporation of a cloud turret, and so resume its growth by settling into a newlyrising mass of air within the cloud bulk. Ludlam (1951, 1952) shows that these conditions are simultaneously satisfied when the particle has a radius of about 150 μ in the case of a water droplet, and a radius of about 300 μ in the case of a graupel

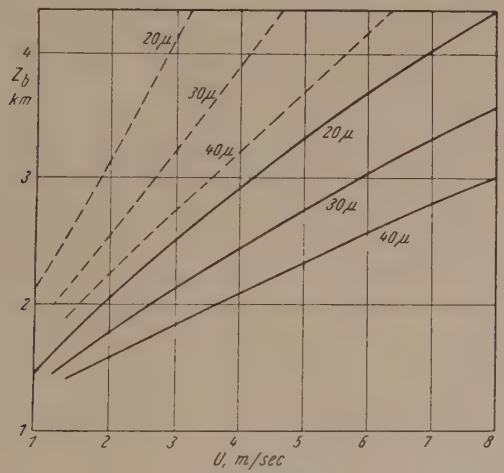

Fig. 6. The variation of the minimum cloud depth z_b for shower development as a function of the updraught U, for initial droplet radii of 20 to 40 μ in clouds with base temperatures of —5°C (pecked lines) and 20°C. (Reproduced by courtesy of the Royal Meteorological Society.)

pellet of meandensity 0.3. Whether or not particles can attain this critical size, and hence the probability of shower formation, will depend on the depth of cloud traversed, in turn determined by the speed of the updraught and the liquid-water concentration which is largely governed by the temperature of the cloud base and the degree of mixing of the cloudy air with the drier environment. In Fig. 6 Ludlam (1951) has calculated the critical minimum depth z_b of a cloud as a function of the uniform updraught U required for droplet of initial radii $r_0 = 20\,\mu$ to 40 μ to produce showers by coalescence in clouds of base temperatures —5°C and 20°C. It is seen that the critical depth of cloud necessary increases considerably with the speed of the updraught and is also somewhat larger for colder clouds and smaller values of r_0. For $r_0 = 20$—30 μ, clouds of only 1.5 to 4 km. depth are required to produce showers by coalescence. The time required is about 30 minutes if $U \simeq 1$ m/sec. and correspondingly less for stronger updraughts.

Fig. 7 shows the variation with base temperature of the minimum cloud depth likely to be associated with showers when the updraughts are weak ($U \simeq 1$ m/sec.) and the critical depths for some other conditions shown on the right-hand side. If the cloud-base temperature exceeds 8°C showers may fall from clouds whose summits do not reach the 0°C isotherm. If the base temperature approaches 20°C the shower-cloud tops are not supercooled even with updraughts of 8 m/sec. On the other hand, in the colder clouds, moderate updraughts may lift the growing drops to heights at which they may freeze.

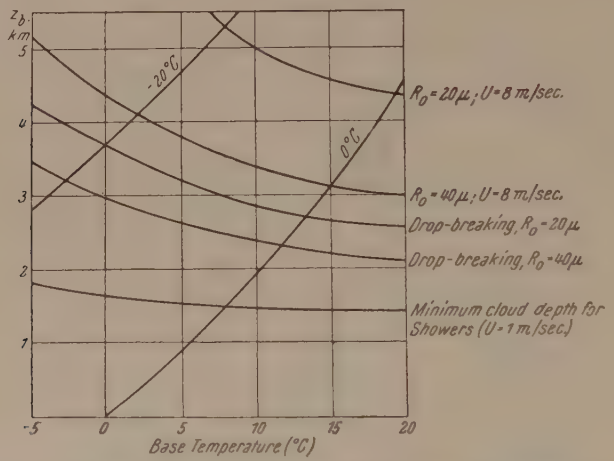

Fig. 7. Occurence of showers produced by the coalescence mechanism in relation to the temperature of the cloud base. The curves show the minimum cloud depths for the various conditions described on the right of the diagram. (Reproduced by courtesy of the Royal Meteorological Society.)

Fig. 6 indicates that clouds having base temperatures above 5°C and updraughts of 1 m/sec. cannot be expected to produce coalescence showers unless they are at least 1500 m. deep: this is borne out by the Australian observations of non-freezing showers in which the updraughts were between 1 and 3 m/sec.

Calculations show that raindrops growing in a cloud in which the updraught exceeds 3 or 4 m/sec. may attain their maximum stable radius of about 2.5 mm. and thereafter break up into a number of large fragments. Now each of these large fragments may continue to grow by coalescence and in turn reach break-up size. Thus in a very deep cloud of high water content it is conceivable that the process might repeat itself a number of times, so that the number of raindrops is rapidly increased by a chain reaction. Some unpublished calculations by the author show that in a cloud with base at 10°C and 900 mb and sustained by a uniform updraught of 7 m/sec., a droplet of 40 μ entering the cloud base would be carried to a further height of 3.5 km. (temperature —10°C) before commencing to fall through the updraught and would attain break-up size (radius

2.5 mm.) at the 3.2 km. level after a total period of 12 minutes. If the disruption is assumed to produce fragments of 1 mm. radius these in turn will grow to break-up size about 3 minutes later after a fall of about 400 m. Successive breakings will take progressively longer so that in the above cloud model the maximum possible number would be six. However these calculations are made on the assumption that the cloud contains the maximum theoretical water content and that this remains constant during growth of the drops. In practice it will be progressively depleted and in consequence the chain reaction will gradually run down. Thus

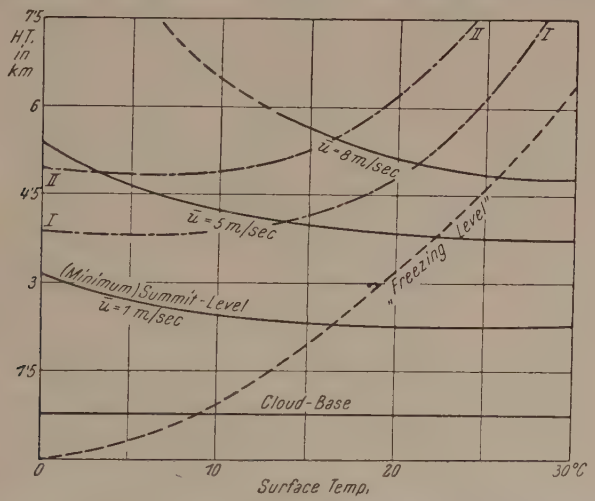

Fig. 8. Approximate variation with surface temperature of the tops of cumulus (base about 1 km.) in which showers may form by coalescence of droplets (when the mean updraught $\bar{U}$ is 1, 5 and 8 m/sec, full lines), and by the growth of ice crystals formed at —10°C (pecked line I) or —20°C (pecked line II) with a mean updraught of 5 m/sec.

even in the centre of a large, warm cumulonimbus it is doubtful whether a drop may undergo more than 3 successive disruptions; these would require more than 20 minutes by which time the original number of raindrops may be increased a thousand-fold and a concentration of rainwater built up sufficient to destroy the updraught and release a shower.

The critical conditions for the release of showers by ice particles have been examined by Ludlam (1951) in much the same way as in the case of the coalescence process. The particles are assumed to grow by sublimation of vapour in the initial stages but having attained a radius of about 100 μ, growth by accretion with supercooled cloud droplets predominates.

The summit levels which cumulus clouds must usually reach to produce a shower by coalescence when the updraught velocity is 1, 5 and 8 m/sec. are shown in Fig. 8. It also shows the summit levels which must be reached if showers are to be released by the growth of ice particles which originate at —10°C (line I) and —20° C (line II) from a cloud with a mean updraught of 5 m/sec. This diagram suggests that

for clouds with base temperatures warmer than 5°C the coalescence process may forestall the ice particles in initiating precipitation, and even though the cloud summits may eventually rise well above the 0°C isotherm this is no clear indication that the presence of the ice phase is essential to the production of a shower.

In a warm, dense cloud small concentrations of ice particles may release a shower in another manner. An ice pellet growing by accretion may collect supercooled water at a rate faster than it can be frozen because the latent heat of fusion cannot be dispersed sufficiently rapidly

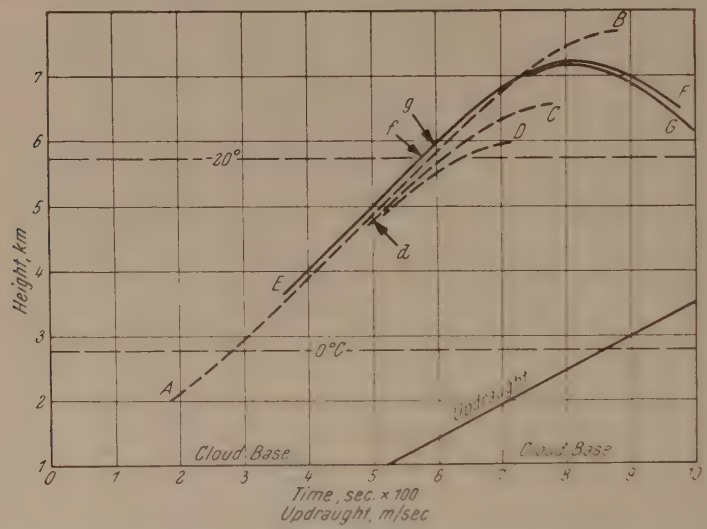

Fig. 9. Growth of precipitation elements in a cloud with base at 900 mb., 10°C., and an updraught increasing from 5 m/sec. at the base to 10 m/sec. above 3.5 km. Droplets of radii 30, 40, and 50 μ at the point A reach a radius of 1 mm. at B, C, D, respectively. Ice particles originating at E (temperature —5°C) are assumed to grow into hailstones of density 0.3 or 0.6 which become wet at F and G with radii 1.0 and 0.6 cm respectively.

to the environment. Thus the pellet may acquire a liquid coat even when the surrounding air is much colder than 0°C and may shed rather large water drops in its wake. The drops may themselves grow by coalescence and even initiate a water-drop chain reaction. Since one wet hailstone may shed several cm^3 of water in the form of drops only a few ice particles (perhaps 1/10 m^3) may be sufficient to initiate a shower under favourable conditions. Fig. 9, taken from a paper by MASON and LUDLAM (1951) describes the growth of ice particles originating at —5°C in a cloud of base temperature 10°C and containing an updraught increasing from 5 m/sec. at the base to 10 m/sec. at 3.5 km. and above. After about 5 mins. the ice crystals have grown into pellets which begin to descend through the updraught; nearly 1000 sec. after the air containing the ice nuclei rose through the cloud base the hailstones have diameters of over a centimetre, their surfaces have become wet at heights where

the outside temperature is below —20°C. Soon afterwards the first-formed hailstones will be able to introduce into the cloud large drops which may commence a chain reaction, even before they have fallen below the 0°C level and have begun to melt. In the same diagram has been traced the history of some large condensation nuclei presumed to be present in the same air which held the efficient ice nuclei. We see that these large nuclei produce 1 mm. drops at about 6 km., and nearly 300 sec. *before* the arrival of the first formed hailstones from above. This again suggests that large condensation nuclei are capable of forestalling the ice particles in initiating a shower.

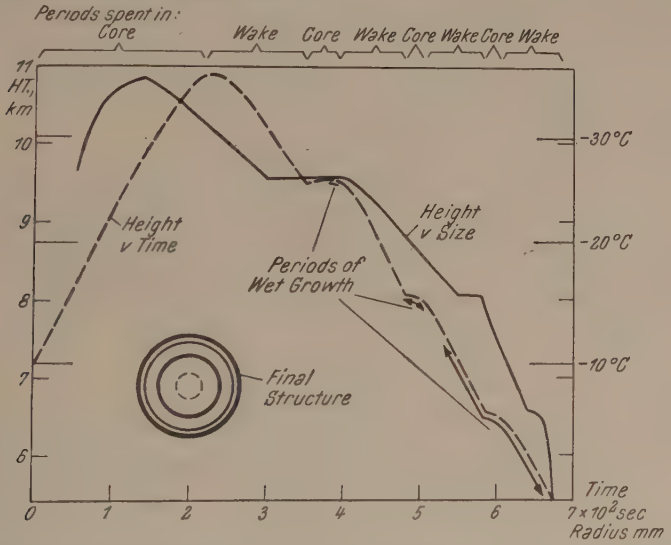

Fig. 10. Calculated growth of hailstone grown upon ice nucleus active at —10°C in a cloud with base at 900mb., and containing bubble cores with upward speed of 20 m/sec. and water content of 6.5 g/m³, separated by vertical distances of 2½ km occupied by wakes with average updraught 5 m/sec. and average liquid water content of 2 g/m³.

This may be a partial explanation of the fact that hail does not occur in all showers, even when in rather cold weather it might be expected to reach the ground before completely melting, and that hail occurs much less frequently over the sea (where the coalescence process may be readily initiated) than in the interiors of continents. The fact that hail was not detected in the majority of the Ohio storms of the Thunderstorm Project may perhaps be attributed to the coalescence process getting under weigh at an early stage as was indicated by the radar evidence (Battan 1953). Hailstorms are believed to occur in clouds containing particularly strong updraughts which may be expected to occur over land where the convective activity is much more intense than over the sea.

If the core of a hailstone consists essentially of a graupel pellet formed by the freezing on impact of the cloud droplets, it will be opaque; when

it acquires a wet skin and part of this water subsequently freezes, a clear layer of ice will be formed. If the element subsequently passes through a region of low water content the droplets may freeze on contact to form a second opaque layer. Thus if the element passes through several successive regions of high and low water content, alternate layers of clear and opaque ice may be formed. This onion-like structure of large hailstones appears to be associated with alternate periods of wet and dry growth in the cores and wakes of successive bubbles within the cloud. The number of concentric layers is generally less than five and the formation of about this number can be explained in terms of the growth of an element inside a single vigorous cell as indicated in Fig. 10 where LUDLAM (1954) has calculated the growth of hailstones passing through the cores and wakes of successive bubbles. Hailstones are shown to grow to a diameter of more than a centimetre within about 11 minutes of the activation of the first ice nuclei.

Occasionally, however, single hailstones of several centimetres diameter consisting of as many as twenty concentric layers are reported. The formation of these very large stones is very difficult to explain. The theory of hail formation is still in its very early stages and probably much more observational data on the conditions under which it occurs and on the dynamical structure of large cumulonimbus is required before much further progress can be made.

Conclusions.

It seems likely that the basic physical processes of precipitation release as shown in Fig. 11 are now fairly well understood: for simple

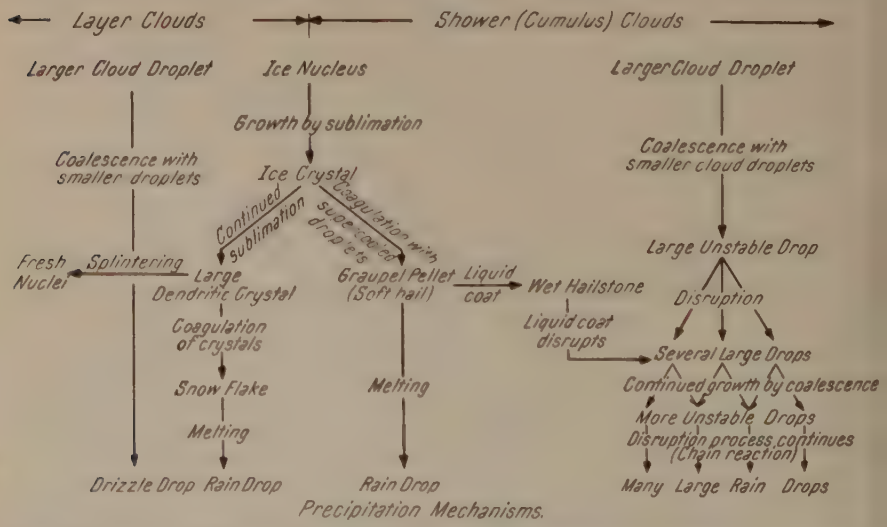

Fig. 11. A schematic diagram of the various mechanisms which may be responsible for the release of precipitation from clouds.

cloud models we can calculate the growth of precipitation elements by the different processes and, in principle, determine which mechanism is likely to predominate under certain conditions. The microphysics of the problem is therefore relatively far advanced, although comprehensive data on the frequency and distribution of ice nuclei and large condensation nuclei which initiate precipitation are urgently required. Further progress is likely to depend very much on future developments in cloud dynamics and a deeper understanding of cloud structure, growth and development in relation to atmospheric motions on at least the synoptic scale. Until we are in a position to use more realistic cloud models it will hardly be worthwhile to replace the above calculations on the growth of a single particle by the much more complicated multi-particle problem in which the interference between growing elements has to be considered.

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Geographical Differences in Cloud Populations.

By

Horace R. Byers.

Summary. Cumulus clouds have been studied by radar and special flight observations with particular reference to the temperatures at which rain is initiated. In the Caribbean area rain starts while the clouds have temperatures greater than $+5^{\circ}$C at their tops, except over heated islands. These results are in sharp contrast with data from New Mexico indicating no rain even when the tops of the cumulus are at temperatures less than -10°C. In the humid areas of the Middle West both above-freezing and below-freezing temperatures characterize the levels of rain formation.

The rate of upward growth of the clouds appears to determine to some extent the height attained before rain initiation. Flight measurements of chloride particles in the atmosphere under favorable conditions show that enough giant-size nuclei can be available to initiate rain by coalescence in the manner hypothetically ascribed to them.

Zusammenfassung. Mittels Radar und Messungen vom Flugzeug aus wurden Cumuluswolken unter spezieller Berücksichtigung der Temperaturverhältnisse, bei denen sich Regen bildet, untersucht. Im Gebiet um Puerto Rico bildet sich Regen, wenn die Wolkenobergrenze bei Temperaturen über -5°C liegt, außer über erhitztem Inselboden. Diese Resultate stehen in schroffem Gegensatz zu Meßergebnissen aus Neu-Mexiko, wo sich kein Regen zeigt, selbst wenn die Obergrenze der Cumuli Temperaturen unter -10°C aufweist. In den feuchten Gebieten des mittleren Westens wird das Niveau der Regenbildung durch Temperaturen sowohl über als auch unter dem Gefrierpunkt gekennzeichnet.

Die Höhe, welche die Wolken erreichen, bevor der Regen ausgelöst wird, scheint in gewissem Ausmaß von der Intensität der Vertikalentwicklung bestimmt zu werden. Flugzeugmessungen zeigen, daß in der Atmosphäre unter günstigen Bedingungen genügend übergroße Chloridkerne vorhanden sein können, um theoriegemäße Regenbildung durch Koagulation auszulösen.

Résumé. La température de formation de la pluie dans des cumulus a été étudiée à l'aide d'un radar et d'observations en plein vol. Dans la région de Puerto-Rico, on observe l'initiation de la pluie bien que la température du sommet des nuages soit supérieure à $+5^{\circ}$C, sauf au dessus des îles. Ces résultats sont tout à fait contraires à ceux du Nouveau-Mexique qui indiquent l'absence complète de pluie

lorsque la température du sommet des cumulus est inférieure à —10°C. Dans les régions humides du Middle-West américain d'autre part, le niveau de formation de la pluie peut être également observé à une température supérieure ou inférieure à la tempèrature de congélation.

La vitesse de développement vertical des nuages semble déterminer l'altitude atteinte avant la formation de la pluie. La présence dans l'atmosphère de particules géantes de chlorures en nombre suffisant pour initier la formation de la pluie par coalescence, selon la théorie proposée, a été établie par des mesures en plein vol.

Introduction.

The Cloud Physics Project at the University of Chicago has been studying convective clouds during the past year, under the auspices of the United States Air Force, Geophysical Research Directorate. A largescale laboratory, field und flight program is being carried out, the main interest centering around the investigation of cumulus clouds at the time they begin to form rain. While the details of cumulus-cloud convection have been studied intensively by MALKUS (1952), LUDLAM and SCORER (1953) and others, the distinguishing feature of our experimental work is that it is concerned more with droplet growth than with the mechanics of convection and that radars have been used extensively to detect precipitation elements in the clouds.

A flight program has been carried out in Puerto Rico and in the Middle West of the United States. The clouds of other regions have been investigated by ground radar and visual measurements by members of the project and their colleagues (see later references). A start has been made toward a *cloud census* in varied geographical environments. The purpose of such a census is to get as much information as possible about the cloud population of a given region and particularly to learn the conditions, especially the temperatures, under which natural rain is initiated. This type of study appears to be the basic requirement of any rational approach to the question of the possibility of artificial inducement of precipitation, as outlined by the author previously (BYERS, 1953).

Cloud Census Data.

BATTAN (1953) has published the results of ground radar measurements of the natural initiation of rain in 123 growing cumulus clouds in Ohio. The temperatures of the tops and bottoms of the first detectable radar echoes, indicating the cloud cores of first growth of raindrops, were tabulated. It was found that 58 per cent of the first echoes had tops warmer than 0°C (bottom temperatures greater than 9°C); 72 per cent had temperatures at the top higher than —4°C (bottom 7°C). No echoes were found which at their initial detection had a temperature at the top less than —16°C. The cloud bases were at 4,000 to 5,000 feet and the freezing level at 12,000 to 15,000 feet, approximately. BATTAN concluded that initiation of rain by the BERGERON-FINDEISEN process was by no means predominant in this middle-latitude region. During the

summer of 1954 similar measurements in Illinois have confirmed these results, and some reasonably exact measurements of the visual tops have been made. The visual data were not obtained in the Ohio measurements.

During the winter and spring of 1954 a more easily interpreted type of cloud census data was taken in Puerto Rico. A similar study has been carried out in the summer of 1954 in the Middle West. In this case the radar was mounted in the nose of an airplane and arranged to scan in a vertical plane parallel to the wing span. While this airplane flew into the cumulus clouds to see if it contained an echo, another fast-climbing plane was flown to the visual top of the cloud to measure its height. Other measurements of cloud properties also were made by the lower plane. The "gain" of the radar was turned quite low so as to detect only the significant echoes at the close range dealt with. The clouds were randomly selected by the pilot of the lower airplane who flew from one cloud to the next according to convenience.

The data of the flights made over the ocean in the vicinity of Puerto Rico are presented in Table I for 499 clouds. It will be noted that 50 per cent of the clouds with the height of the visual top of the cloud at 9,000 to 9,499 feet (temperature 7,9°C) had echoes. All clouds having a temperature at the top as low as +5°C produced echoes. The cloud base was at about 2,000 feet and the freezing level at 12,000 to 14,000 feet, approximately.

Over the island of Puerto Rico other results were obtained, as shown in Table II. Here the data were taken somewhat differently. Since air traffic conditions over the island did not permit instrument flying at random, the radarcarrying airplane had to fly above the clouds and measure their tops. The sample obviously is too small, but there can be no doubt that the differences between these clouds and those over the water are real.

Another region, studied by ground radar by BRAHAM, REYNOLDS and HARRELL (1951), is New Mexico. The data, not reproduced here, show that echoes do not form there in cumulus clouds except where the temperature is considerably below freezing. The explanation given for this regional difference by BYERS, BATTAN and BRAHAM (1953) is that the cloud bases are so high that there is insufficient cloud volume below the freezing level to permit warm rain coalescence. The cloud bases are at 10,000 to 12,000 feet and the freezing level at 13,000 to 15,000 feet. It was pointed out by the authors that at the time of first formation of an echo, the vertical thickness (base to top) of the New Mexico clouds is about the same as that of the Ohio clouds.

During the summer of 1954, cloud census flights like those of Puerto Rico have been made in the Mississippi Valley region. The preliminary data show that only 11 per cent of the clouds studied had radar echoes when the cloud tops were at temperatures greater than 0°C. These were visual tops, however, and up to this time (October 1954) the examination of the radar film has not been completed, so it is not known at what temperatures the radar echoes themselves were formed.

Table I

Over-Water Cloud Census

Cloud Top Height	Clouds Examined	Clouds With Radar Echoes	% With Radar Echoes
5,000— 5,499	10	0	0
5,500— 5,999	20	0	0
6,000— 6,499	53	1	2
6,500— 6,999	51	2	4
7,000— 7,499	58	6	10
7,500— 7,999	63	8	13
8,000— 8,499	55	11	20
8,500— 8,999	38	10	26
9,000— 9,499	48	24	50
9,500— 9,999	36	15	42
10,000—10,499	22	15	68
10,500—10,999	20	14	70
11,000—11,499	6	5	83
11,500—11,999	6	6	100
12,000 and over	13	13	100

Total of 12 Flights — 499 Clouds

Table II

Over-Island Cloud Census

Cloud Top Height	Clouds Examined	Clouds With Radar Echoes	% With Radar Echoes
5,000— 5,499	0	0	0
5,500— 5,999	0	0	0
6,000— 6,499	0	0	0
6,500— 6,999	3	0	0
7,000— 7,499	23	3	13
7,500— 7,999	38	3	8
8,000— 8,499	47	13	27
8,500— 8,999	21	5	24
9,000— 9,499	22	5	23
9,500— 9,999	7	1	14
10,000—10,499	9	3	33
10,500—10,999	7	4	57
11,000—11,499	3	1	33
11,500—11,999	2	0	0
12,000 and over	9	4	44

Total of 3 Flights — 191 Clouds

Some Explanations.

With regard to tropical cumulus clouds, it has been observed that 1) they grow more slowly than, and 2) produce rain when much smaller than middle-latitude cumulus. These two characteristics are related, for the coalescence processes that can occur in "warm" clouds are time-consuming, and if the cloud grows slowly the coalescence may have time to produce raindrops long before the top reaches the freezing level. In fast-growing clouds, the visual top may go quite high before the coalescence has had time to proceed very far. These indications are illustrated in the differences in the overwater and overisland cloud census data of Puerto Rico. The island gets hotter than the ocean during the day and provides energy for rapid growth of cumulus which then penetrate to considerable heights before the echo is formed. Part of the contrast with Middle West clouds may be due to this effect.

An explanation of the coalescence put forth by Woodcock (1950, 1952) and others (e. g. Ludlam, 1951) is based on the existence of giant salt nuclei, 10^{-9} gm and larger, which at saturation form droplets sufficiently large to fall at an appreciably different rate from that of the prevailing cloud droplets and to collide and coalesce with them.

Measurements of chloride particles at the ground and on airplane flights have been made by the Cloud Physics Project. The techniques used are described elsewhere by Lodge. Of the giant nuclei, some

hundreds per cubic meter were found in Puerto Rico both at the ground and at cloud levels. Measurements reported at Champaign, Illinois (BYERS, BRAHAM and BATTAN), some 800 miles from the nearest salt water, showed on the average only one or two giant nuclei per cubic meter at ground level. Recently, however, some flights have been made between Illinois and the Gulf of Mexico with strong inflow of air aloft the Gulf showing hundreds of giant chloride particles per cubic meter even as far as 600 miles inland. One must admit, then, the possibility that this type of initiation of coalescence can take place over the continent.

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Wirkungsbereiche und Häufigkeit der natürlichen Gefrierkerne.

Von

W. Rau.

Mit 14 Textabbildungen.

Zusammenfassung. Die in den Wolken stark verbreitete Unterkühlbarkeit des Wassers sowie die Wirkungsweise der Gefrierkerne wurden im Laboratorium untersucht. Dabei wurden im Gefrierkernspektrum Maxima bei —4, —11 bis —12 und —19° C gefunden. Änderungen der Untersuchungsbedingungen beeinflussen nur die Höhe, nicht aber die Temperatur der Maxima. Auch eine künstliche Beeinflussung des Spektrums ist möglich und äußert sich in gleichem Sinne. Die stärkere Unterkühlbarkeit kleiner Tropfen (im 3. Maximum) wird als rein statistischer Volumeneffekt erkannt. Wäßrige Lösungen zeigen das Gefrierkernspektrum um die Gefrierpunktserniedrigung verschoben. Diese Ergebnisse sowie die nachgewiesene allgemeine Gültigkeit des Gefrierkernspektrums führen zu dessen Deutung durch temperaturbedingte Strukturänderungen des Wassers; sie erklären die deutlich erkannte Bevorzugung derselben Temperaturbereiche bei der atmosphärischen Niederschlagsbildung, was keine der bisherigen Niederschlagstheorien vermag.

Der Gefrierkerngehalt des Wassers wird bestimmt und es wird nachgewiesen, daß diese früh wirkenden Kerne auch im natürlichen Aerosol in genügender Anzahl vorhanden sind. In den verschiedenen Luftmassen werden sehr unterschiedliche Gefrierkerngehalte festgestellt: polare Luftmassen enthalten viele und sehr früh wirkende Gefrierkerne, in rein subtropischen Luftmassen fehlen diese nahezu vollständig. Daraus ist auf maritimen Ursprung dieser Gefrierkerne zu schließen.

Zwischen —40° und —50° C, je nach erfaßter Luftmasse, vereist die Mischwolke ganz, nach einem schon früher einsetzenden Anstieg der Eisteilchenzahl. Dabei sind wieder Gefrierkerne beteiligt, und zwar etwa 200 per cm^3. Der für die homogene Keimbildung charakteristische starke Anstieg der Eisteilchenzahl tritt erst bei Annäherung an —70° C auf. Die hier gebildete kubische Modifikation des Eises wird durch neue Beobachtungen belegt.

Schließlich wird noch die kernfreie Eiskeimbildung durch dielektrische Polarisation erwähnt, welche bei geringer Unterkühlung ausgelöst werden kann, die mechanischen Gefrierauslösungen erklärt und auch in der Atmosphäre vorkommen muß.

Summary. The supercooling of water which is found most frequently in clouds, as well as the mechanism of action of freezing nuclei were investigated in the

laboratory. The spectrum of freezing nuclei was found to have maxima at —4, —11 to —12 and —19°C. Alterations of the investigation conditions influence only the height but not the temperature of the maxima. Also an artificial influence on the spectrum is possible, and it has the same effect. The fact that small droplets can be supercooled to lower temperatures (in the 3rd maximum) is proved to be merely a statistical volume-effect. Aqueous solutions show the spectrum of freezing nuclei displaced by the lowering of the freezing point. These results and the ascertained general validity of the spectrum of freezing nuclei lead to its interpretation by changes of the structure of water itself, which are determined by temperature. They explain the fact that the formation of atmospheric precipitation prefers the same regions of temperature whereas none of the hitherto existing precipitation theories can do that.

The content of freezing nuclei in water is determined, and it is shown that these early active nuclei are also present, in a sufficient number, in the natural aerosol. The contents of freezing nuclei found in various air masses show a great variation: polar air masses contain many and very early active freezing nuclei; these are nearly entirely absent in subtropical air masses. Thence it is concluded that these freezing nuclei are of maritime origin.

Between —40° and —50°C, according to the investigated air mass, the mixed cloud, consisting of crystals and droplets, freezes entirely, following an increase of the number of ice particles which takes place somewhat earlier. Freezing nuclei participate in this process, again, their number being of the order of 200 cm^3. The strong increase of the number of ice nuclei which is characteristic for the homogeneous formation of particles, takes place only if the temperature approaches —70°C. The cubic modification of ice formed at this temperature is proved by further observations.

Finally, we mention the formation of ice particles bare of nuclei by dielectric polarisation which can be caused at slight supercooling. It explains the mechanical release of freezing, a process which should also occur in the atmosphere.

Résumé. L'eau surfondue, un état très fréquent dans les nuages, et la manière dont les noyaux glaçogènes agissent pour former de la glace ont été l'objet de recherches au laboratoire. Au cours de ces expériences, le spectre des noyaux glaçogènes montrait des maxima aux températures de —4, —11 à —12 et —19°C. Des changements dans les conditions expérimentales n'influencent que la hauteur mais pas les températures des maxima. Une influence artificielle sur le spectre est possible et se manifeste dans le même sens. Le fait que des gouttelettes plus petites peuvent être surfondues à des températures plus basses, fut décelé comme n'étant qu'un effet statistique causé par le volume.

Les solutions aqueuses montrent aussi le spectre des noyaux glaçogènes, mais le spectre y est déplacé par l'abaissement du point de cristallisation. Ces résultats et la validité commune du spectre des noyaux glaçogènes impliquent l'explication de ce spectre par les changements de la structure de l'eau elle-même par la température. Ils expliquent aussi la préférence des mêmes températures lors de la formation des précipitations atmosphériques, ce qu'aucune théorie à ce sujet n'a pu faire jusqu'ici.

En mesurant le contenu de l'eau en noyaux glaçogènes on trouve que l'aérosol naturel contient aussi un nombre suffisant de ces noyaux à effet précoce. Dans les diverses masses d'air, le contenu en noyaux glaçogènes est très différent: les masses d'air polaires en contiennent un grand nombre à effect très précoce, dans les masses d'air subtropicales ces noyaux manquent presque complètement. Il s'en suit que ces noyaux glaçogènes sont très probablement d'origine maritime.

Entre —40 et —50°C, suivant l'origine de la masse d'air en question, les nuages mixtes, composés de cristaux de glace et de gouttelettes d'eau, gèlent complètement après augmentation préalable du nombre des particules de glace, à laquelle participent de nouveau des noyaux glaçogènes à raison d'environ 200 par cm^3. L'augmentation intensive du nombre des particules de glace, caractéristique pour la formation homogène, ne commence qu'en s'approchant de —70°C; de nouvelles observations confirment qu'à cette température se forme une modification cubique de la glace.

L'auteur discute encore la formation de la glace par la polarisation diélectrique qui se fait sans noyaux. Elle produit des germes de glace à des températures peu inférieures à 0°C, explique les nucléations mécaniques et doit aussi exister dans l'atmosphère.

Die Mischwolke aus Eiskristallen und Wassertropfen, welche dem Bergeronschen Prozeß der Niederschlagsbildung zugrunde liegt, kann nur existieren, weil das Wasser unterkühlbar ist. Ihre Eiskristalle müssen heterogen gebildet sein. Homogene Keimbildung kann nicht vorliegen; sie würde in kurzer Frist alle Tröpfchen in Eis verwandeln, das Mischwolkenstadium mit seinen günstigen Wachstumsbedingungen somit beendigen. Da außerdem die von Wegener postulierten Sublimationskerne, welche bei Eissättigung schon den Wasserdampf direkt ansublimieren sollten, nicht aufgefunden werden konnten, kommen als Keimhilfen nur Gefrierkerne in Frage. Damit reduziert sich das Problem der wolkenphysikalisch wichtigen Eisbildung auf die Suche nach den Gefrierkernen und die Bestimmung ihrer Eigenschaften. Die Ergebnisse solcher Untersuchungen vermitteln einen Einblick in die Vorgänge bei der natürlichen Eisbildung und bilden damit die physikalische Grundlage, von der jeder Versuch einer künstlichen Beeinflussung und die Beurteilung des Erfolges auszugehen hat.

I. Das natürliche Gefrierkernspektrum und seine künstliche Beeinflussung.

Unterkühlbarkeit ist nicht auf das Wasser beschränkt, sondern tritt bei sehr vielen Schmelzen auf. Infolge der hohen Kristallisationsgeschwindigkeit des Wassers wächst aber schon der erste Eiskeim durch das ganze Volumen hindurch. Die freiwerdende Erstarrungswärme verhindert sogar weitere Keimbildungen. Man muß daher die übliche Bestimmung des Kristallisationsvermögens durch Auszählung der bei bestimmten Unterkühlungen vorhandenen Keime durch eine Statistik über viele Einzelvolumen ersetzen. Kühlt man, zugleich in teilweiser Analogie zur Wolke, große Tropfen auf blanker Metallunterlage ruhend in einer geschlossenen Kältekammer, damit Unterlage und umgebende Luft dieselbe Temperatur haben, so ergibt sich die in Abb. 1, Kurve 1, dargestellte Keimbildungshäufigkeit.

Im einzelnen ist zu beobachten:

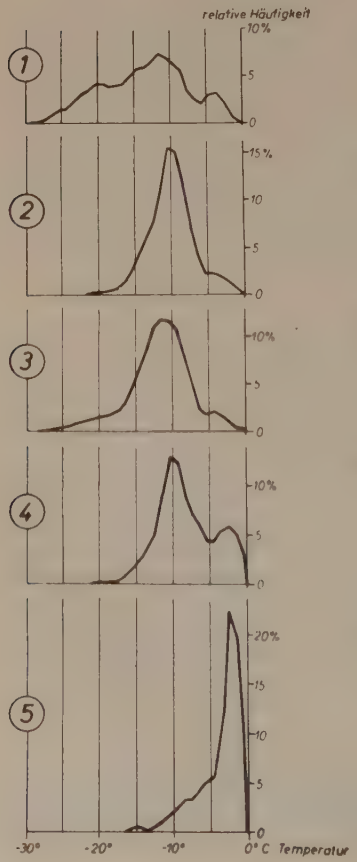
1. Bei mehrfach wiederholtem Gefrieren und Wiederauftauen kommt es häufig vor, daß ein Tropfen mehrmals bei derselben Temperatur und von derselben Stelle aus erstarrt. Hier muß also ein Gefrierkern sitzen.

2. Ein Gefrierkern kann inaktiv werden. Dies ist daran zu erkennen, daß die Erstarrungstemperatur tiefer rückt und der Eiskeim an anderer Stelle auftritt.

3. Wichtiger als diese Alterung der Gefrierkerne ist die Tatsache, daß Gefrierkerne wieder aktiv werden können, wenn sie abtrocknen. Dies tritt fast ausschließlich am Rand auf, und man kann durch Entfernen solcher Randkerne wieder das spätere Gefrieren erzielen.

Diese Erscheinungen berechtigen dazu, die oben geschilderte Keimbildungshäufigkeit als das Spektrum der Gefrierkerne zu deuten. Sie bewirken aber auch, daß der Verlauf dieses Spektrums von der Vorgeschichte der Gefrierkerne abhängig ist. Die Bevorzugung der 3 Temperaturbereiche um —4, —12 und —19° C bleibt dabei erhalten und beweist, daß dem Gefrierkernspektrum eine allgemeine Bedeutung zukommt.

Werden die Tropfen nur einmal gefroren und dann wieder frische verwendet, so fällt die Alterung weg, damit auch das 3. Maximum, das 2. wird um so steiler (Abb. 1, Kurve 2). Mehrmalige Verwendung derselben



„Natürliches" Gefrierkernspektrum bei starker Alterung (1943) 240 Beob.

Gefriereinsatz bei jeweils ersten Kühlungen

Spektrum bei iterierten Kühlungen mit erhöhtem Kerngehalt (Kernalterung) 1230 Beob.

Spektrum bei Fremdkernzugaben 3638 Beob.

Gefrierkernspektrum bei Zugabe *frischer* Kerne (Kristalline und amorphe Substanzen)

Abb. 1. Gefrierkernspektrum bei verschiedenen Versuchsbedingungen.

Tropfen verbreitert das 2. Maximum (Kurve 3). Werden noch natürliche Fremdsubstanzen (kein Ag I oder dergl.) in die Tropfen gebracht, so wird das 2. Maximum steil und auch das 1. tritt stärker auf (Kurve 4). Kommen diese Substanzen möglichst fein gepulvert und scharf getrocknet in die unterkühlten Tropfen, so erhält man überhaupt nur noch das erste Maximum (Kurve 5). Die Art der Substanz spielt keine wesentliche Rolle. Diese Wirkungen der Vorgeschichte der Kerne sind besonders wichtig, weil sie im Einzelfall bei gleichem Kerngehalt zu verschiedenen Ergebnissen führen und auch in der Atmosphäre von selbst möglich sind. Insbesondere sind Inversionen durch frühe Eisbildung ausgezeichnet (Abtrocknungseffekt).

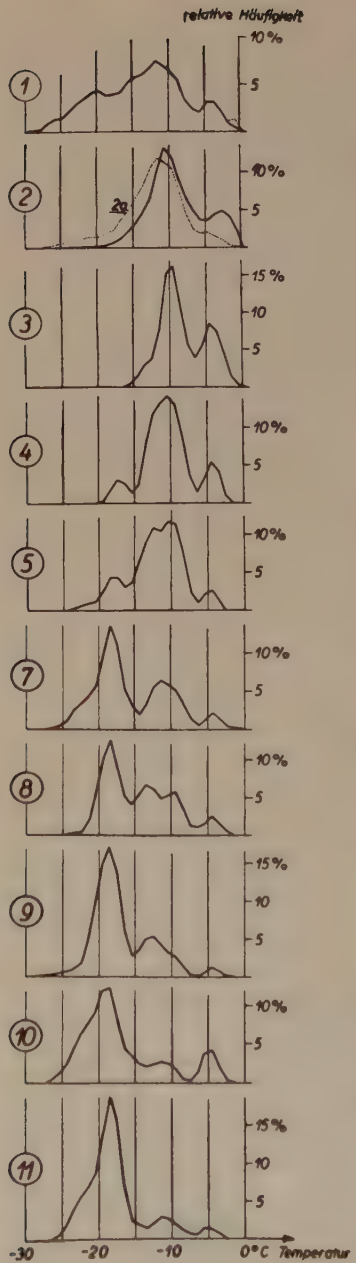
II. Der Gefrierkerngehalt des Wassers.

Infolge der zwangsläufigen Bevorzugung der besten Gefrierkerne entspricht der experimentell ermittelte Verlauf des Gefrierkernspektrums nie dem wahren Gefrierkerngehalt. Nur bei Entfernung der besten Kerne, etwa durch Destillation oder durch Alterung, können auch späterwirkende Kerne in Erscheinung treten und es tritt das 3. Maximum auf. Weit wirksamer ist jedoch eine stärkere Unterteilung (Abb. 2).

Je kleiner die untersuchten Tropfen werden, desto mehr sinkt das Hauptmaximum ab und die Erstarrungen im 3. Maximum nehmen zu. Daraus folgt, daß die Kerne im 2. Maximum relativ selten sind. Die Abnahme des 2. Maximums mit dem Tropfenvolumen entspricht den Wahrscheinlichkeitsgesetzen und beweist damit, daß die stärkere Unterkühlbarkeit kleiner Tropfen ein rein statistischer Volumeneffekt ist, der auf die Beteiligung von Gefrierkernen zurückgeht und diese ausdrücklich beweist. Aus der Abnahme des 2. Maximums ist ferner abzuleiten, daß ein hier ansprechender Gefrierkern im Mittel in 10 bis 30 mm^3 Wasser anzutreffen ist. Dabei handelt es sich um doppelt destilliertes Wasser. Die Zahl der Kerne im 1. Maximum hängt ganz von den Versuchsbedingungen in der Kammer und im Arbeitsraum ab. Kerne des 3. Maximums sind sehr zahlreich, mindestens 1 pro 0.01 mm^3 Wasser. Genauere Angaben sind darüber aus dem Spektrum nicht möglich, da dieser Eisbildungsbereich nur knapp berührt wird.

III. Der Gültigkeitsbereich des natürlichen Gefrierkernspektrums.

Weitere experimentelle Untersuchungen ergaben, daß das Gefrierkernspektrum ganz allgemein gilt. Es erwies sich unabhängig von der Tropfenunterlage, von der Vorbehandlung des Wassers durch elektrische Felder, Funkenüberschläge, schwache Ströme, Ionenvermehrung usw. sowie vom Reinheitsgrad. Sehr stark verunreinigtes Wasser erstarrt allerdings häufiger im 1. Maximum. Auch die Herkunft der Wasserproben ist ohne Einfluß, auch in atmosphärischen Niederschlägen tritt es auf. Diese Kerne sind also auch in der Atmosphäre vorhanden, brauchen jedoch bei der Bildung der Niederschläge nicht beteiligt gewesen zu sein. Sogar bei der sonst



Tropfengröße: 600 mm³
Kurve 1: Normale Kernalterung
(240 Beob.)

Tropfengröße: 600 mm³
Kurve 2: Teilweise Impfung durch frische Kerne
(4628 Beob.)
Kurve 2a: Iterierte Kühlungen bei gleichbleibendem erhöhtem Kerngehalt
(1230 Beob.)

Tropfengröße: 200 mm³
(234 Beob.)

Tropfengröße: 80 mm³
(135 Beob.)

Tropfengröße: 32 mm³
(528 Beob.)

Tropfengröße: 11 mm³
(360 Beob.)

Tropfengröße: 4 mm³
(684 Beob.)

Tropfengröße: 1 mm³
(702 Beob.)

Tropfengröße: 0.15 mm³
(324 Beob.)

Tropfengröße: 0.015 mm³
(243 Beob.)

Abb. 2. Gefrierkernspektrum und Tropfengröße.

üblichen Untersuchung an in Glasröhrchen eingeschmolzenen Wasserproben kann dasselbe Spektrum nachgewiesen werden, desgleichen in den Ergebnissen anderer Arbeiten, vor allem in den ausführlichen Beobachtungen von Dorsey.

IV. Gefrierkerngehalt des natürlichen Aerosols.

Nur in künstlich erzeugten Wolken sind diese früh wirkenden Gefrierkerne bisher meist nicht gefunden worden. Die einzigen Beobachtungen von Findeisen und später von Weickmann und Aufm Kampe mit 2 bzw. 18 m^3 fassenden Kammern ließen den Eindruck entstehen, daß diese Kerne in der Atmosphäre zumindest in bodennaher Luft sehr selten seien. Das trifft nicht zu. Die später ansprechenden Kerne sind wohl viel häufiger, die frühen Kerne lassen sich aber mit einer 30-l-Kammer noch gut feststellen, wenn die Beobachtungsmethode entsprechend ausgebaut wird. Die Temperaturabhängigkeit der Gefrierkerndichte in einer verbesserten Mischwolkenkammer zeigt Abb. 3. Der mittlere Gefrierkerngehalt pro Liter bodennaher Luft beträgt 50 wirksame Kerne bei —10° bis —12°C und 400 bei —20°C. Sein Temperaturverlauf stimmt mit dem Gefrierkernspektrum überein.

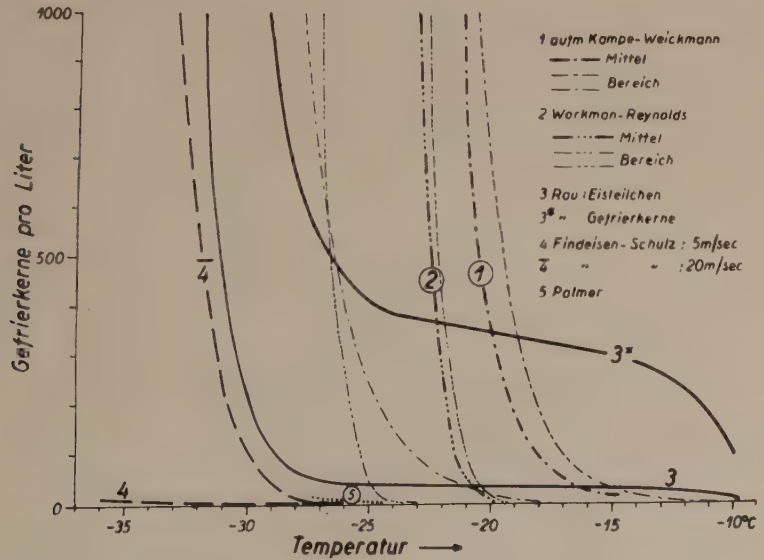


Abb. 3. Gefrierkerngehalt des natürlichen Aerosols.

V. Eisbildung in unterkühlten Wolken.

Nach diesen Ergebnissen kann die Übereinstimmung zwischen dem Gefrierkernspektrum und der atmosphärischen Eisbildung, auf die wir

schon lange hingewiesen haben, nicht mehr überraschen (Abb. 4). Nach PEPPLER hat die Häufigkeitsverteilung der Temperatur in reinen Eiswolken (1c) ein Maximum bei —18°C. Die häufigste Temperatur für stärkeren Vereisungsbeginn in unterkühlten Wolken liegt bei —12°C über dem europäischen Festland (1b). Die Zahl der unterkühlten Wolken, ohne beobachtete Eisteilchen, fällt mit sinkender Temperatur vom Gefrierpunkt aus rasch ab (1a). Bei Rauhfrostbildung auf dem Säntis sind die Temperaturen —4° und —10°C ausgezeichnet (1d). Die in der PEPPLERschen Unterkühlungskurve latent enthaltene Eisbildung nahe 0°C hat SCHWERDTFEGER über See direkt nachgewiesen. Dort tritt Schauerbildung meistens schon ein, wenn die Wolkenobergrenze im Sommer —4°C erreicht. Die Jahreskurve zeigt die Temperaturen —4 und —12°C bevorzugt. Diese Angaben lassen sich durch neuere Untersuchungen immer wieder belegen, z. B. von HOWELL (3a und 3b) oder

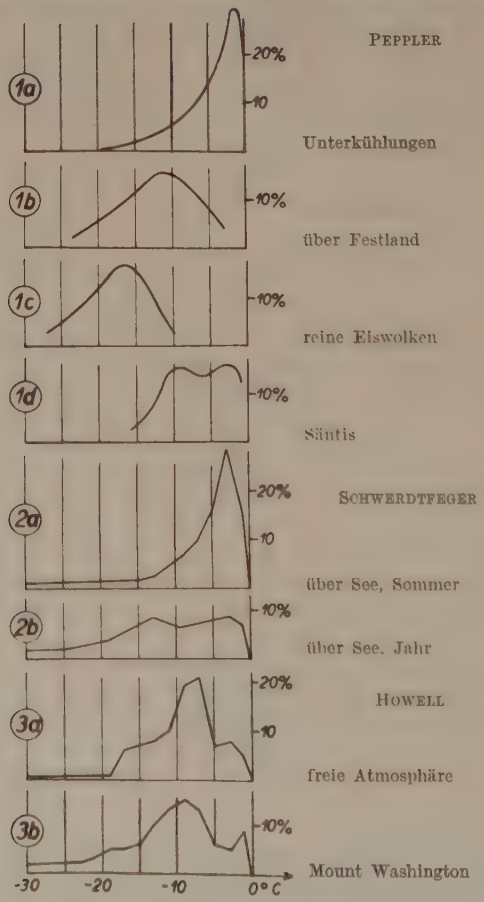


Abb. 4. Verteilung der atmosphärischen Gefriertemperaturen.

besonders eindrucksvoll durch die Ergebnisse von Bossolasco an Bergstationen (Abb. 5). Immer sind dieselben Temperaturbereiche ausgezeichnet.

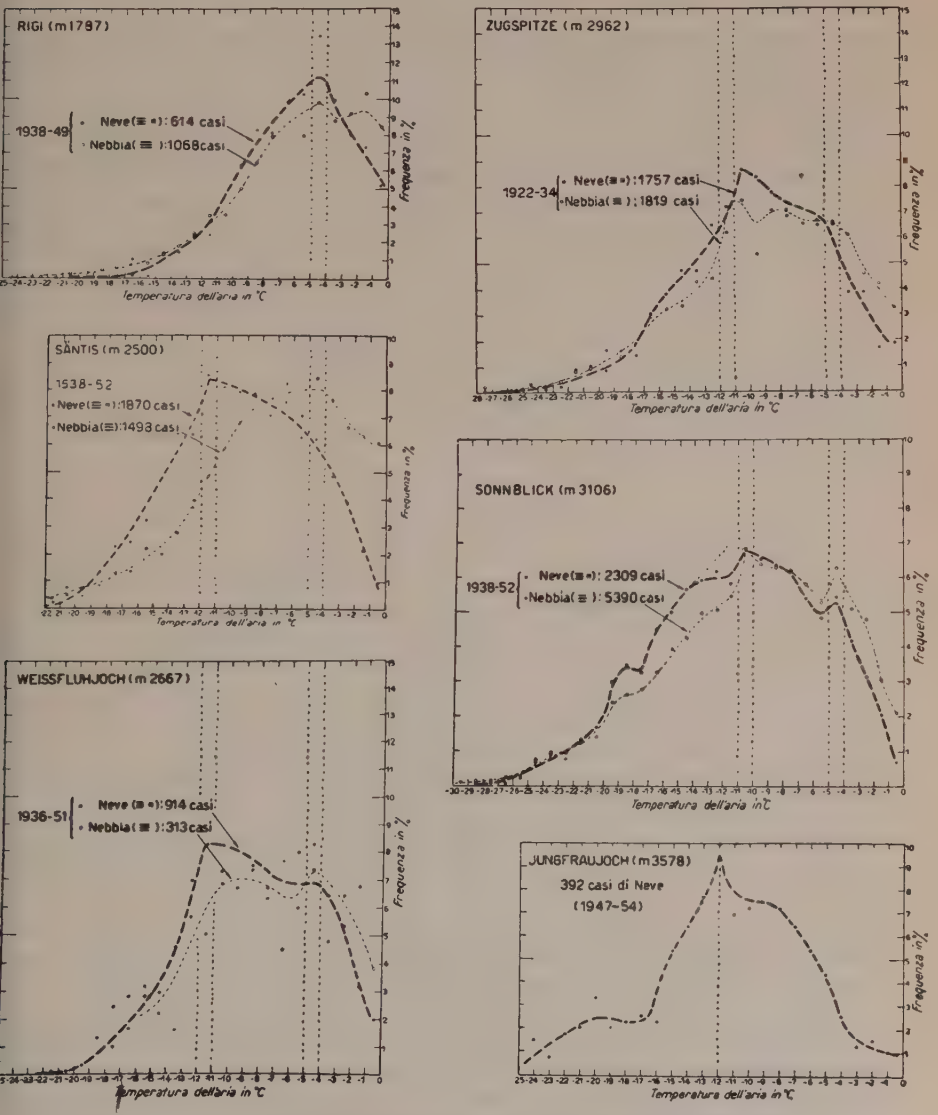


Abb. 5. Verteilung der Lufttemperatur an Bergstationen bei Schneefall und Nebel bzw. unterkühltem Nebel allein (nach M. Bossolasco).

VI. Ursache des Gefrierkernspektrums.

Diese allgemeine Gültigkeit des Gefrierkernspektrums zwingt dazu, eine besondere innere Ursache anzunehmen. Daß die Gefrierkerne immer in der entsprechenden Verteilung vorkommen sollen, befriedigt nicht, weil bei jeder Art von Wirkungsmechanismus durch Größenunterschiede und dergleichen Einflüsse bei so einem umfangreichen Material viel eher eine gleichmäßige Verteilung ohne Maximum auftreten sollte. Der Vergleich mit anderen Schmelzen, wo ebensolche Keimbildungsmaxima auftreten und auch bei offensichtlich heterogenen Bildungen der Substanz selbst zugeschrieben werden, führt zu dem Schluß, daß auch hier das Wasser für die beiden späteren Maxima verantwortlich ist. Bei —12°C ist der Dampfdruckunterschied über Wasser und über Eis am größten. Die Häufungsbereiche sind zudem dadurch ausgezeichnet, daß im 1. Nadeln, im 2. Platten und Sterne und im 3. schließlich prismatische Formen entstehen und aufwachsen. Zur Bildung dieser polymorphen Keime sind Strukturänderungen des Wassers nötig. Diese sind aber längst bekannt und zur Erklärung der verschiedenen Anomalien des Wassers herangezogen worden, so für das Dichtemaximum, dessen Druckabhängigkeit, die Gefrierausdehnung und den Polymorphismus bei hohen Drucken. Man kann daher gar nicht mit einer konstanten Wasserstruktur bei der Eisbildung rechnen.

VII. Gefrierkernspektrum in wässerigen Lösungen[1].

In einer Reihe von wässerigen Lösungen wurde nachgewiesen, daß das Gefrierkernspektrum auch hier auftritt, allerdings um die Gefrierpunktserniedrigung zu tieferen Temperaturen verschoben. Da bei Konzentrationen, welche geringer als die eutektische sind, reine Eiskristalle ausfallen, müßten Gefrierkerne mit festen Ansprechtemperaturen auch in Lösungen das Spektrum in der üblichen Lage hervorrufen, nur der Bereich der Gefrierpunktserniedrigung wäre abgeschnitten. Das ist nicht der Fall. Die gelösten Moleküle bewirken offenbar die Verschiebung des Gefrierkernspektrums über eine Strukturänderung des Wassers. Das steht damit in Einklang, daß sie auch das Dichtemaximum in wässerigen Lösungen zu tieferen Temperaturen rücken, was beim reinen Wasser durch Druckerhöhung, d. h. wieder Strukturänderung, erzwungen werden kann.

Wolkenphysikalisch von Interesse ist das Ergebnis, daß bei NaCl in eutektischer Lösung das 3. Maximum nach —40°C rückt, wo wieder eine besondere Eiskeimgrenze liegt.

Werden Salzlösungen als Tropfen untersucht, so wird die eutektische Temperatur nicht unterschritten. Hier tritt sehr stark das 1. Maximum in Erscheinung, verursacht durch Abdampfen und Kristallisation am Tropfenrand. In zugeschmolzenen Röhrchen kann durch entsprechende Kühlung auch ein Vorherrschen des 1. Maximums erzielt werden; die Kristallisation tritt am Meniskus ein.

[1] W. RAU, ZS. f. Naturforschg., **9**, 939, 1954.

VIII. Gefrierkerngehalte der verschiedenen Luftmassen[1].

Bisher fehlt noch die Feststellung, ob der Gefrierkerngehalt immer so konstant ist, wie er in den beschriebenen Untersuchungen herauskam. Zeitliche Schwankungen würden Auskunft über die noch unbekannte Natur und Herkunft der Gefrierkerne geben. Solche Schwankungen treten tatsächlich auf. Abb. 6 zeigt die Temperaturabhängigkeit der Eisteilchenbildung für mehrere Tage vor- und nachmittags. Eine bestimmte Gefrierkernzahl ist immer da, aber sie wird bei ganz verschiedenen Temperaturen erreicht. Man gibt daher den Gefrierkerngehalt nach Anzahl und Güte zweckmäßig durch eine entsprechende Bezugstemperatur an, z. B. die Temperatur T*, bei der in unserer Kammer 200 Eisteilchen ausfallen. Diese Grenze ist sehr scharf, und 1°C Änderung kann schon 100 und mehr Prozent Änderung im Gefrierkerngehalt ausmachen.

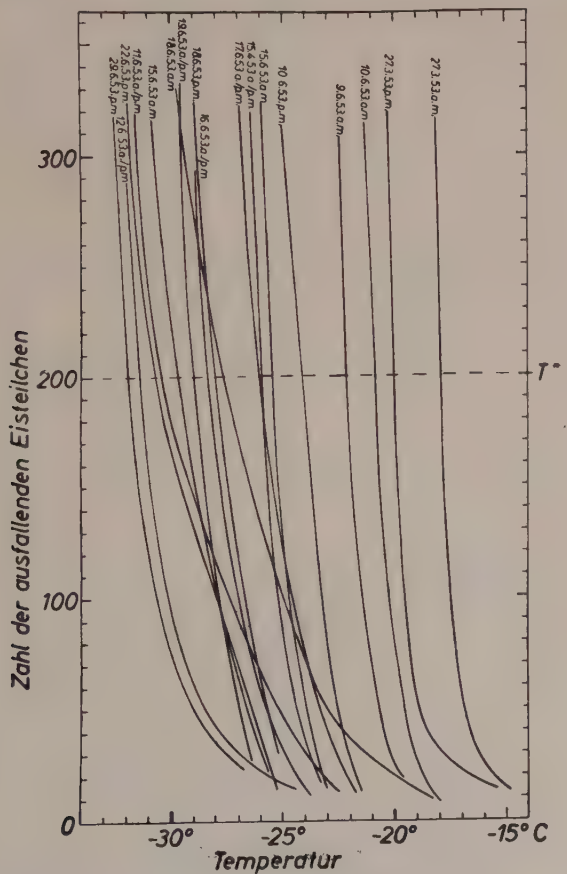


Abb. 6. Gefrierkerngehalt an verschiedenen Tagen.

[1] W. Rau, Met. Rundsch., 7, 205, 1954.

Die Häufigkeitsverteilung dieser Bezugstemperatur T* (Abb. 7) für 14 Monate Registrierungen reicht von —18°C bis —43°C, ein Maximum liegt bei —24°C, ein weiteres bei —41°C.

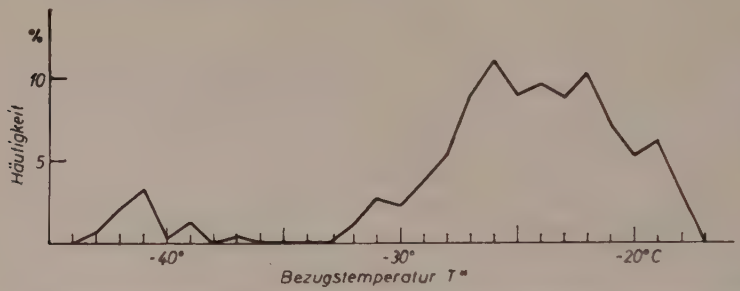


Abb. 7. Häufigkeitsverteilung der Temperatur T*, bei der die Eisteilchendichte 1/cm³ eintritt.

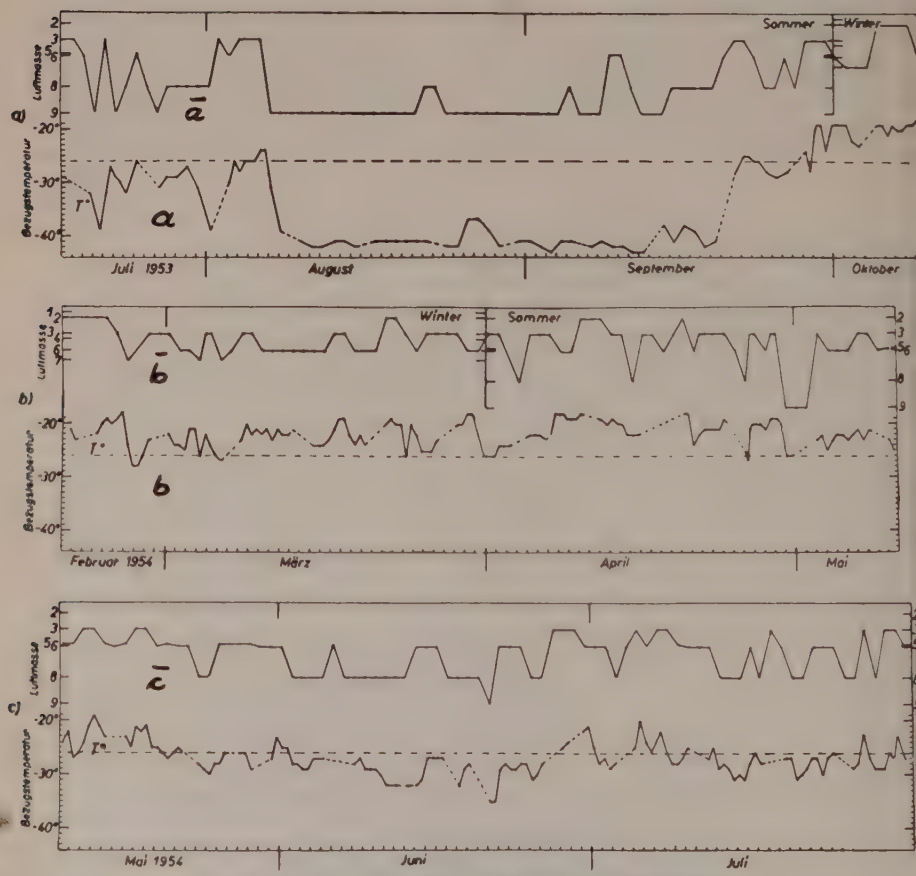
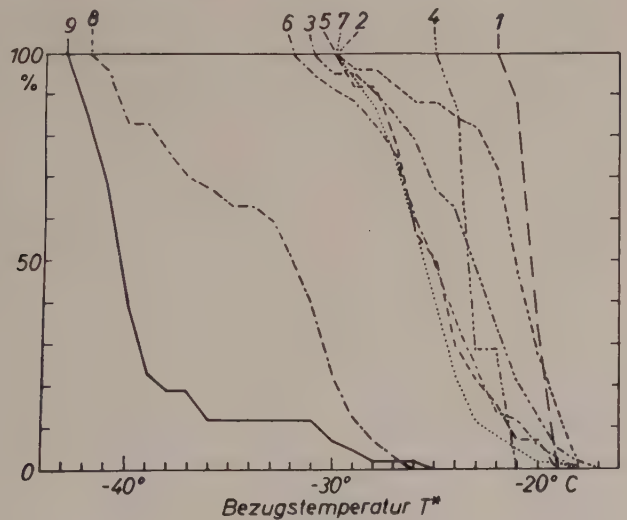


Abb. 8. a, b, c Zeitlicher Verlauf des Gefrierkerngehalts.
ā, b̄, c̄ Luftmassenwechsel relativ (siehe Text).

Der zeitliche Verlauf des Gefrierkerngehalts (= der Bezugstemperatur T*) bei täglich zwei Bestimmungen, den Abb. 8 für drei Intervalle von je acht Wochen zeigt, läßt deutlich einen systematischen Gang erkennen, vor allem das Absinken auf etwa —40°C und den späteren Wiederanstieg im August, September 1953.

Korrelationen zu den meteorologischen Elementen: der Temperatur und Feuchtigkeit der Luft, dem Barometergang, der Sichtweite, dem Niederschlag, der geographischen Verteilung der Zyklonen und Antizyklonen, waren nicht aufzufinden. Auch die Gefrierkernwindrose zeigte nicht ein ausgeprägtes Ergebnis, wie es bei den Kondensationskernen vorkommt. Die üblichen örtlichen Kern- bzw. Ionenproduktionen waren ohne Wirkung. Daraus ist zu folgern, daß diese Gefrierkerne nicht anthropogenen Ursprungs sind wie die Mehrzahl der Kondensationskerne. Auch kontinentale Kernquellen können nicht in Frage kommen, sonst sollten stärkere lokale Witterungseinflüsse feststellbar sein.

Ganz ausgeprägt ist aber der Zusammenhang mit der Luftmasse, und zwar bringt Polarluft immer eine hohe Zahl früher Kerne, während (maritim) subtropische Luft, die warme Antizyklone, die späten Bezugs-



Luftmassen.

1 Kontinental subtropisch (Winter)
2 Kontinental polar (Sommer und Winter)
3 Maritim polar (Sommer und Winter)
4 Kontinental gemäßigt (Winter)
5 Kontinental gemäßigt und subtropisch (Sommer)
6 Gealterte Polarluft (Sommer und Winter)
7 Maritim gemäßigt und subtropisch (Winter)
8 Maritim gemäßigt (Sommer)
9 Maritim subtropisch (Sommer)

Abb. 9. Gefrierkerngehalt und Luftmasse, Jahresverteilung.

temperaturen liefert. Dieser an Extremfällen erkennbare Zusammenhang ist auch statistisch zu fassen. Die Kurven der Abb. 9 zeigen für verschiedene Luftmassen in der Verteilung über ein Jahr die Wahrscheinlichkeit dafür, daß die Bezugstemperatur vor bestimmten Werten liegt, daß somit ein bestimmter Gefrierkerngehalt vorliegt. Das Material ist teilweise für Sommer und Winter unterteilt. Im Winter ist der Gefrierkerngehalt höher, und die Unterschiede zwischen den Luftmassen sind geringer als im Sommer. Auch im Mittel ist der Kernreichtum der polaren Luftmassen und die Kernarmut der (maritim) subtropischen nachzuweisen. Die kontinental subtropische Luft kam selten vor, ihr Kernreichtum ist deshalb nicht gesichert. Die anderen Luftmassen reihen sich dazwischen ein.

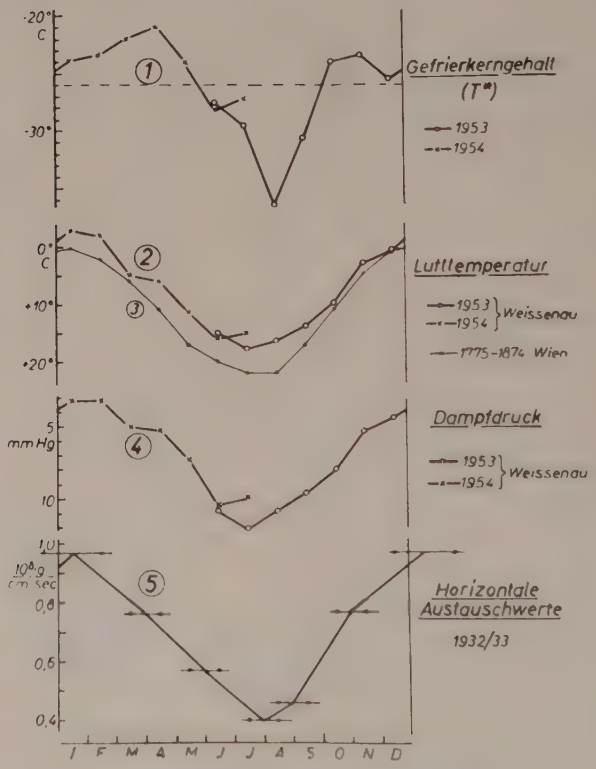


Abb. 10. Jahresgang des Gefrierkerngehaltes.

Stellt man die einzelnen Luftmassen durch ihren einjährigen mittleren Gefrierkerngehalt (= mittlere Bezugstemperatur) dar, so zeigt deren zeitlicher Gang (Kurve a, b, c in Abb. 8) den täglichen „Sollbetrag" an Gefrierkernen an, während die Kurven a, b, c den tatsächlichen Gehalt angeben. Beide Kurvenzüge stimmen fast ausnahmslos miteinander überein, und zwar auch c und c, für welche diese Skala rein prognostisch

angewandt wurde, da diese Werte nicht zur Ermittlung der Skala verwendet worden sind.

Der Jahresgang des Gefrierkerngehalts (Abb. 10, 1) verläuft antiparallel zur Temperatur (2,3) und dem Wasserdampfgehalt (4). Da direkte Korrelationen fehlen, ist zu schließen, daß beide Gänge eben durch das unser Klima erzeugende Spiel zwischen polarer und subtropischer Luft zustande gebracht werden, was durch den konformen Verlauf des horizontalen Austauschkoeffizienten (5) gewährleistet erscheint.

Diese Gefrierkerne in Dichten von 10 und mehr pro cm^3 sind offensichtlich polaren Ursprungs. Da ein künstliches Sprühaerosol aus Meerwasser ebenfalls den Einsatz bei —18°C erbrachte, ist an Lösungskerne maritimen Ursprungs zu denken, deren Entstehung und Verfrachtung in polaren Luftmassen begünstigt wird.

Wichtig ist noch die Folgerung, daß diese zeitlichen Schwankungen bei Vergleichen zwischen Gefrierkerngehalten immer berücksichtigt werden müssen.

IX. Eiskeimbildung bei —40° C und homogene Eiskeimbildung[1].

Meteorologisch weniger interessierend, weil sie erst bei tiefen Temperaturen vorkommt, dafür aber theoretisch wichtig ist die homogene Keimbildung, vor allem die Ansicht, daß sie bei —40°C einsetzen soll, weil hier das Mischwolkenstadium in künstlichen Nebeln aufhört.

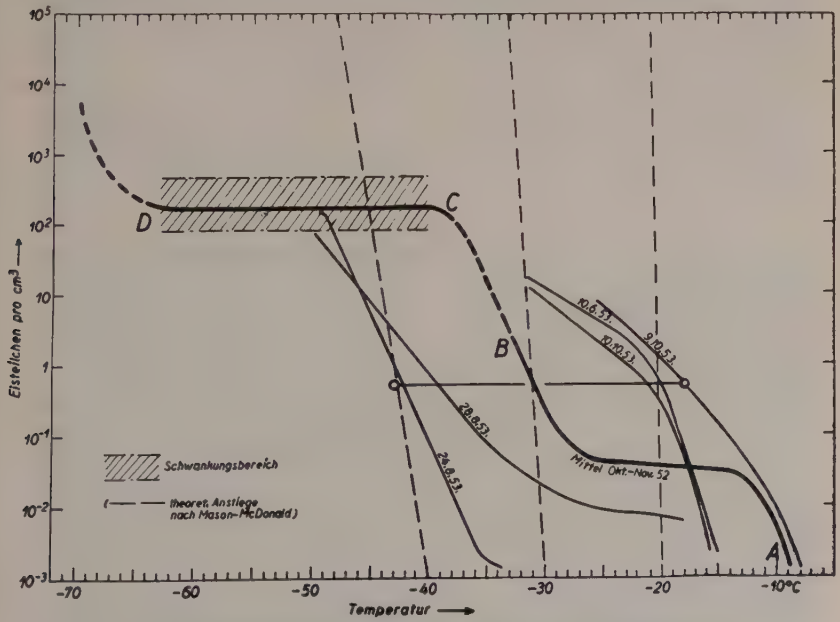


Abb. 11. Eiskeimbildung bei tiefen Temperaturen und Gefrierkerngehalt.

[1] W. RAU, Geofisica pura e applicata, **28**, 201, 1954.

Diese Beobachtung konnte mit unserer 30-l-Kammer bestätigt werden. Aber der als Beweis für homogene Keimbildung angeführte starke Anstieg der Eiskeimbildung wurde nicht gefunden. An photographischen Aufnahmen der Wolken ausgezählt, ist die Eisteilchenzahl zwischen —40 und —65°C praktisch konstant und beträgt etwa 200 Eiskristalle pro cm³ (Abb. 11).

Erst mit Annäherung an —70°C tritt ein unverkennbar starker Anstieg ein. Die Eiswolken haben dann weiche, runde Formen, können bei derselben Aufnahmetechnik nicht mehr aufgelöst werden und schweben bei —80°C stundenlang unverändert in der Kammer.

Damit müssen bei —40°C noch Gefrierkerne beteiligt sein. Dies kann durch zeitliche Schwankungen belegt werden. In Subtropikluft setzte die Eisbildung so spät ein, daß z. T. bei —43°C erst 1 Eisteilchen pro cm³ vorhanden war und die Wolke erst bei —50°C völlig vereiste. In Polarluft setzt der starke Anstieg schon bei —18°C ein, biegt aber um und erreicht bei —40°C dieselbe konstante Teilchenzahl (Abb. 11, mit

Abb. 12. Kubische und hexagonale Eiskristalle in Taubeschlägen bei tiefen Temperaturen.

Tagesangaben). Homogene Keimbildung kann keine derartigen Temperaturunterschiede aufweisen.

Dieses Ergebnis steht mit unseren Beobachtungen an Taupunktsflächen in Einklang, wo bis —72°C Tröpfchenbeschlag, darunter aber direkte Sublimation in kubischer Kristallform vorkam. Der Einwand, daß Verunreinigung durch Alkohol vorgelegen haben müsse, wird durch die in Abb. 12 wiedergegebene neue Beobachtungsfolge[1] widerlegt.

Eine massive, von Trockeneis umgebene Metallkammer, wird auf —50 bis —60°C gekühlt. Ein halbzylinderförmiger, nach außen offener, kleiner Hohlkörper wird mit flüssiger Luft noch stärker gekühlt. Dabei entsteht ein koagulierender Tröpfchenbelag, der bei —72°C mit leichter Trübung erstarrt. Hierauf tritt plötzlich Eis in kubischen Dendritformen auf (Abb. 12, Bild a). Beim Erwärmen dampfen die Kristalle ab und vereinigen dabei den wieder flüssig gewordenen Belag zu größeren Tröpfchen (b). Dadurch tritt die Auflagefläche der Kristalle dunkel hervor. Bei erneuter Kühlung wiederholt sich die Erscheinungsfolge. Läßt man aber weiter erwärmen, so treten bei —40°C hexagonale Eisbildungen mit starken Überdampfhöfen auf (c). Kondensiert man schon bei höherer Temperatur, so treten die bekannten hexagonalen Sterne auf (Bild d); und das alles bei derselben Kammerfüllung. Dies ist nur durch Modifikationsänderungen des Wassers zu verstehen.

In der Atmosphäre wird die homogene Keimbildung normalerweise nicht beteiligt sein. Ihre Anwendung auf die Perlmutterwolken bleibt unberührt bestehen.

X. Eiskeimbildung durch dielektrische Polarisation.

Eine andere kernlose Keimbildung kann aber unter speziellen Bedingungen vorkommen. Starke elektrische Felder verursachen das Gefrieren des unterkühlten Wassers, was im Experiment einfach vorzuführen ist. Man braucht dazu nur einen Funken auf den Tropfen überschlagen zu lassen (Abb. 13, a) oder aber im Tropfeninnern durch Spitzenwirkung ein genügend hohes Feld zu erzeugen (b) und die Eisbildung tritt sofort ein. Je nach Versuchsbedingungen entsteht eine sehr große Anzahl von Eiskristallen, die in Richtung der Feldlinien orientiert sind. Das Wasser muß rein, d. h. mehrfach destilliert sein. Auch Regenwasser aus Starkregen erwies sich als genügend rein (chemisch). Sonst kann das Feld im Tropfeninnern gar nicht aufgebaut, d. h. die dielektrische Polarisation nicht erzielt werden, welche man für die Keimbildung direkt verantwortlich machen kann. Starke Felder in Gestalt von elektrischen Doppelschichten, wie sie vom sogenannten Lenard-Effekt bei positiven Temperaturen bekannt sind, sind auch für die mechanische Gefrierauslösung verantwortlich zu machen, z. B. dann, wenn ein scharfer Luftstrahl in einen unterkühlten Tropfen geblasen wird und

[1] Ausführliche Veröffentlichung in Vorbereitung.

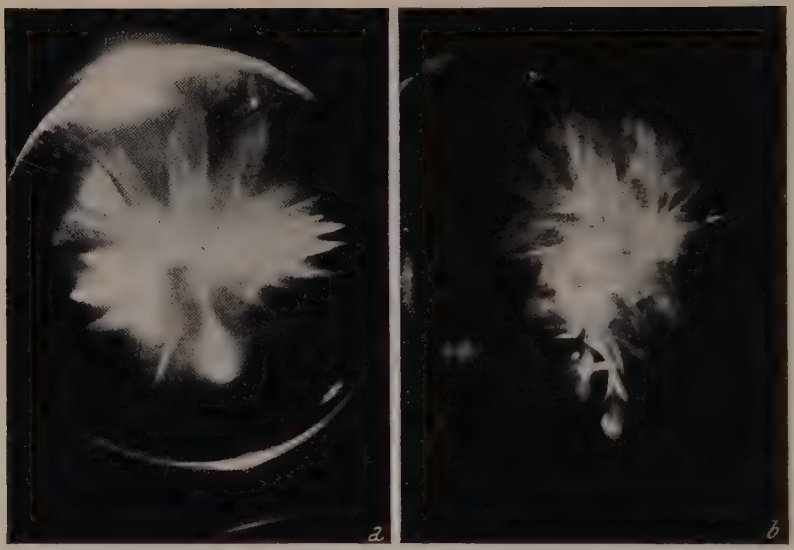


Abb. 13. Eiskeimbildung durch dielektrische Polarisation.

Abb. 14. Eiskeimbildung durch Zersprühen.

eine Unzahl von Eiskeimen entsteht (Abb. 14). Wichtig ist, daß diese Keimbildung nur ganz schwache Unterkühlung benötigt. Zersprühen von Wassertropfen erzeugt nicht nur hohe Felder, sondern beim unter-

kühlten Zustand auch Eiskeime, vermutlich mit gesteigerter elektrischer Tönung. Kerne sind dabei nicht beteiligt.

Schließlich ist mit der dielektrischen Polarisation auch die impfende Wirkung trockener Substanzen aus der elektrischen Doppelschicht zwanglos zu erklären, die sich beim Eindringen ins Wasser ausbildet und in einer Ausrichtung der Wasserdipole beruht, welche die Keimbildungsarbeit leisten kann.

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Diese Arbeiten enthalten weitere Literaturnachweise.

551.510.42:551.510.41

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Détermination de la nature chimique des aérosols.

Par

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Résumé. L'auteur discute brièvement les résultats obtenus à la suite de l'étude de quelques types de particules microscopiques et submicroscopiques au moyen de la réaction de LIESEGANG et de procédés de sensibilisation. En même temps il indique quelles possibilités il y a lieu d'attendre de la réaction de LIESEGANG et de certains processus particuliers dans la gélatine pour l'étude des aérosols atmosphériques.

Zusammenfassung. Es wird kurz über die Ergebnisse berichtet, die bei der Untersuchung einiger Arten mikroskopischer und submikroskopischer Partikel mit Hilfe der LIESEGANGschen Reaktion und von Sensibilisierungsprozessen gefunden werden; dabei wird auf die Möglichkeiten hingewiesen, die die LIESEGANGsche Reaktion und spezielle Prozesse in Gelatine für die Erforschung atmosphärischer Aerosole bieten.

Summary. The results found in investigations on some kinds of microscopic and submicroscopic particles, performed by means of the LIESEGANG reaction and of processes of sensibilisation, are referred. There is pointed at the possibilities arising from the LIESEGANG reaction and from special processes in gelatine for the investigation of atmospheric aerosols.

Riassunto. Si riportano brevemente i risultati ottenuti nello studio della rivelazione di alcuni tipi di particelle microscopiche e submicroscopiche per mezzo della reazione di LIESEGANG e dei processi di sensibilizzazione utilizzati: si accenna alla possibilità che la reazione di LIESEGANG e reazioni particolari in gelatina offrono per l'indagine sugli aerosoli atmosferici.

Un aperçu des méthodes courantes qui permettent de repérer la nature chimique des particules microscopiques et ultramicroscopiques, conduit aux résultats suivants.

L'examen morphologique *au microscope électronique* permet de remonter de la structure cristallographique de la particule à sa nature chimique, pratiquement sans limite de sensibilité: je veux dire par là que, avec les échelles d'images actuellement obtenues, aucune particule n'échappe à l'examen: au contraire, à ma connaissance, la sensibilité relative aux

différences dans la structure cristallographique des particules de nature chimique différente est insuffisante, spécialement à cause des variations qui interviennent dans l'état de la particule pendant les opérations de mesure [*1*, *2*, *3*, *4*].

Dans un récent travail FACY [*5*] a obtenu des résultats satisfaisants en utilisant des techniques particulières dans la méthode de *dessèchement* des noyaux dans la chambre du microscope électronique: toutefois le procédé de mesure est long et laborieux.

L'examen spectroscopique individuel est relatif à la détection des noyaux constitués par le sel de sodium, grâce à la couleur caractéristique de la lumière émise par les vapeurs de cet élément excitées avec une flamme appropriée. Mais il résulte que la sensibilité de la méthode de détection est telle qu'elle limite à 10^{-4} cm le diamètre des particules chiffrables.

Des procédés relatifs au *développement chimique* sur des particules capturées sur du papier filtre soumis à un traitement particulier ont été utilisés très souvent, et il semble, avec des résultats satisfaisants bien que la sensibilité de détection concerne les particules microscopiques.

Un procédé développé à l'observatoire de Monte Cimone, actuellement en élaboration, permet, dans certains cas, la détection de la nature chimique des particules *ultramicroscopiques*: la méthode est basée principalement sur une *réaction chimico-physique* particulière dans le gel de gélatine, réaction observée par R. LIESEGANG (1896): quelques substances solubles, soit sous forme de particules solides, soit en solution sous forme de gouttelettes très concentrées, réagissent avec des sels dissous dans un gel de gélatine étendu en film sur un support, donnant une réaction caractéristique: le précipité, produit de la réaction, forme *un petit anneau* autour du point de contact. Les anneaux de LIESEGANG ne sont, en général, pas visibles au microscope en champ clair à cause des très faibles dimensions des petits cristaux du précipité, mais ils sont bien visibles en lumière latérale.

Les lois chimico-physiques de la réaction particulière ne sont pas bien connues: on peut dire que le point de choc de la particule sur la gélatine devient un centre générateur d'ions qui émigrent radialement dans la gélatine: la réaction avec les ions du sel dissous dans la gélatine se produit au bout d'un certain temps et, de ce fait à une distance appréciable du centre: si le gel de la gélatine est parfait, la distribution du précipité est nettement annulaire.

La méthode de la détermination de la nature chimique des aérosols que j'exposerai est basée sur la réaction de LIESEGANG et sur des procédés analogues; mais je parlerai auparavant des techniques développées pour des mesures à effectuer sur des aérosols naturels et, dans la dernière partie, des techniques pour l'examen des aérosals artificiels, en portant une attention particuliére à ceux de AgI auxquels nous nous intéressons davantage.

Les réactions de LIESEGANG ne permettent généralement pas la détection de particules à masse inférieure à 10^{-12} gr. L'étude relative à la recherche de la solution à mettre dans la gélatine pour pousser la réaction

jusqu'à 10^{-15} gr. et, dans certains cas au-delà, consiste principalement à obtenir un anneau constitué par un précipité fortement coloré, ou colorable au moyen de procédés de sensibilisation chimico-physique: ceci parce que la vision en lumière latérale ne permet pas la détection des anneaux relatifs aux particules ultramicroscopiques.

Avant de décrire les techniques chimiques utilisées, je montrerai le système dont nous nous servons pour la capture des aérosols: comme on sait, les systèmes de capture à gicleur ne permettent pas d'obtenir une efficacité passable pour des particules qui ont un diamètre inférieur ou égal au micron. Le système que nous avons utilisé est celui de *capture à effluve* que nous avons réalisé, soit pour des prélèvements à terre dans l'observatoire de Monte Cimone, soit pour des prélèvements par avion.

Pour obtenir la haute tension à bord de l'avion, on a utilisé un élévateur électronique. Une sensibilisation particulière de la réaction de LIESEGANG concernant les particules qui donnent en solution l'ion Cl (chlorures solubles) a été obtenue pour la détection de masses d'environ 10^{-15}—10^{-16} gr. On prépare un gel de gélatine contenant en solution un sel d'argent soluble ($AgNO_3$): Les anneaux de LIESEGANG relatifs à la réaction sont formés par le chlorure d'argent: si l'on soumet le petit verre à la lumière on peut provoquer dans le petit anneau (soit sur le bord, soit à l'intérieur) la réduction de l'argent métallique de l'halogénure: selon la quantité de radiation absorbée les particules d'argent ont une épaisseur différente de sorte que l'anneau même prend une coloration qui va du jaune au noir.

Des mesures effectuées dans l'observatoire de Monte Cimone en utilisant deux techniques différentes pour la détection des chlorures (l'une avec une sensibilité telle qu'elle permet de déceler seulement les gros noyaux [*6*] et l'autre avec la méthode que j'ai indiquée ci-dessus) ont montré la présence dans l'atmosphère de gros noyaux en nombre très variable qui semblent, après l'examen d'une série de mesures effectuées pendant 6 mois, être en relation avec le type de masse d'air examiné (ce nombre variant d'un maximum de 120.000 particules de chlorure à quelques unités par m^3 d'air). Avec la méthode à haute sensibilité, on a repéré de 10^6 à 10^8 particules de chlorure par m^3. Tandis que cette dernière mesure confirme que la plupart des noyaux contenus dans l'atmosphère proviennent de la mer, les mêmes observations indiquent une faible variabilité du nombre, ce qui donnerait à penser que les gros noyaux seulement peuvent être indicatifs des caractères de la masse d'air en observation.

Parmi les procédés chimiques développés selon la réaction de LIESEGANG relative aux particules qui, semble-t-il, constituent l'aérosol atmosphérique, la technique de détection des particules qui donnent en solution l'ion SO_4 (acide sulfurique et sulfates solubles) présente un certain intérêt. Il n'est pas possible, dans ce cas (du moins, je n'ai pu y réussir) d'obtenir une haute sensibilité, et l'on ne peut procéder qu'à l'observation des gros noyaux, car il y a peu d'électrolytes qui donnent un précipité avec l'ion SO_4.

On prépare le gel de gélatine en dissolvant en solution un sel soluble de Ba; le produit de la réaction, le sulfate de Ba, prend la forme d'un petit anneau selon la réaction de LIESEGANG.

Quelques mesures effectuées en laboratoire ont démontré que les produits de combustion du bois contiennent un grand nombre de particules qui, en solution, donnent l'ion SO_4. Les mesures effectuées ont fait apparaître une haute variabilité du nombre de gros noyaux dans l'atmosphère. La technique pour procéder à la mesure des particules de sulfate n'est pas des plus simples parce que les dimensions des granules du précipité qui constitue le petit anneau de LIESEGANG varient sensiblement en fonction de la température du gel. Les brusques fluctuations de température constituant une possibilité de déformation des petits anneaux, on préfère utiliser pour le gel de l'agar-agar.

Pour déceler les particules issues des produits de combustion de substances organiques (substances qui donnent en solution l'ion ammonium) on a mis au point la réaction de LIESEGANG par la préparation d'un gel de gélatine contenant en solution le réactif de NESSLER; la préparation de la gélatine n'est pas facile parce que l'hydrate de potassium contenu dans le réactif de NESSLER détruit les propriétés gélifiantes de la gélatine animale. Il est encore possible d'obtenir de bons résultats avec un gel d'amidon soluble.

La sensibilité de la réaction est assez élevée, car le précipité de réaction a une coloration rouge écarlate caractéristique. La détection des sulfures solubles est également possible avec une sensibilité élevée. Les mesures effectuées dans l'atmosphère n'ont pas fait découvrir la présence de particules de sulfure.

Les carbonates solubles peuvent de même être détectés, mais avec une sensibilité moindre, telle qu'on l'obtient par ultramicroscopie, car je n'ai pas réussi à obtenir un précipité fortement coloré.

Notons que le système de la réaction de LIESEGANG ne permet pas, en général, une évaluation exacte des diamètres des noyaux qui ont provoqué la réaction elle-même; les dimensions de l'anneau dépendent de l'état physique de la gélatine. Pour quelques observations, spécialement en ce qui concerne les noyaux de chlorures, je chercherai à établir une échelle du système avec des mesures systématiques au moyen d'un microscope électronique. Par la comparaison des mesures effectuées avec les noyaux obtenus artificiellement, je crois qu'il doit être possible d'évaluer les dimensions des particules contenues dans l'atmosphère; mais maintenant je dois dire, qu'à cause des différentes sensibilités, je ne crois pas pouvoir obtenir des résultats très précis.

Les observations sur les degrés de sensibilité atteints ont été faites sur la base de la comparaison des diamètres des gouttelettes artificielles obtenues en arrosant des solutions connues de chlorure et mesurées avec une technique microphotographique à flash, les anneaux issus de la capture des noyaux de sel constituant le résidu de l'assèchement de ces gouttelettes.

J'ai cherché la possibilité de sensibiliser aussi la détection des par-

ticules qui provoquent la réaction de LIESEGANG formant un précipité blanc et permettant la vision des anneaux uniquement par ultramicroscopie. J'ai utilisé à cet effet le système d'exciter la fluorescence des anneaux eux-mêmes en introduisant dans le gel de gélatine des sels opportunément choisis, soit pour obtenir un précipité fluorescent, soit pour qu'en solution reste un ion métallique luminogène, apte à augmenter la puissance même de l'excitation. J'ai obtenu quelques résultats dans la détection des sulfates, mais la variabilité du résultat obtenu dans les différents essais m'ont fait penser à la présence d'un paramètre très critique et peu facile à évaluer; je crois qu'une étude approfondie de cette question pourrait donner de bons résultats.

Pour ce qui est des aérosols artificiels, j'ai développé à fond une technique qui permet la détection des particules submicroscopiques d'un sel d'argent soluble obtenues par sublimation de vapeur et ayant les mêmes caractères de diffusion dans l'air que les particules de Ag I sortant d'un brûleur. Les particules qui donnent en solution l'ion Ag ne se trouvent pas dans l'atmosphère. Il est donc possible d'étudier les modalités de diffusion des particules submicroscopiques obtenues par sublimation de vapeur.

La technique de détection des particules de $AgNO_3$ permet d'atteindre une sensibilité très élevée, allant certainement jusqu'à 10^{-16} gr. Cette réaction de LIESEGANG sensibilisée est possible en préparant un gel de gélatine contenant en solution un sel qui engendre l'ion Cl. Le précipité de réaction, le chlorure d'argent, forme un petit anneau visible à l'ultramicroscope. Cette réaction est susceptible de sensibilisation lorsqu'on provoque par la lumière la réduction de l'halogénure dans le précipité. L'augmentation ultérieure de la sensibilité a été obtenue en incorporant dans le gel de gélatine des substances spéciales, capables de provoquer des précipités de copulants fortement colorés, conséquence de l'action réductrice du chlorure d'argent: tout cela sans soumettre la plaquette de verre à aucun bain. Il s'agit en substance d'une application particulière des techniques de développement chromogène en usage dans la chimie des formateurs.

Dans le gel de gélatine contenant en solution du NaCl on dissout une certaine quantité de chlorhydrate de diméthyl-paraphénylène-dyamine asymétrique (env. 3 gr. par 1000 cm^3 d'eau utilisée pour dissoudre la gélatine) et une solution d'un formateur dans l'acétone ou dans l'alcool éthylique (2 gr. env. de formateur pour 100 cm^3 de dissolvant); la solution du formateur doit être ajoutée à la gélatine chaude, préparée comme décrit, dans la proportion de 1 : 10 du poids d'eau utilisée pour dissoudre la gélatine. La solution doit être alcalinisée avec du sulfite de sodium et du carbonate avant d'être additionnée à celle du formateur en solution dans le dissolvant organique. Une fois les petits anneaux obtenus, le procédé de réduction par la lumière provoque dans les environs des germes d'argent l'oxydation de la diméthyl-paraphénylène-dyamine qui réagit avec le formateur en formant un copulant coloré insoluble.

J'ai obtenu deux types de gélatine, l'un pour les anneaux colorés en

rouge, en utilisant comme formateur un dérivé pirazolonique (1 phényl-3 méthyl-5 pirazolone) et l'autre pour les anneaux colorés en bleu-vert en utilisant l'α naphtol. Un premier essai de semence de Monte Cimone vers la vallée du Pô a donné des résultats très satisfaisants, tant au point de vue fonctionnement de capture à effluve de bord d'un avion, qu'à celui du système de détection des particules. On se propose avec ce système d'étudier les modalités de diffusion dans l'atmosphère de particules submicroscopiques semées par brûleur.

Pour ce qui est de la détection des particules de Ag I, on ne peut plus parler de réaction de LIESEGANG, parce que la réaction de LIESEGANG se rapporte aux sels solubles alors que le Ag I est pratiquement insoluble.

Une réaction qui dérive de celle de LIESEGANG pour la détection des particules de Ag I a été obtenue en provoquant la formation d'ions complexes contenant de l'argent dans de la gélatine, puis la précipitation de l'argent avec le sulfure de sodium.

La forme du précipité n'est pas celle d'un anneau, mais d'une petite tache ronde. On peut chercher à obtenir de meilleures formes de précipité en provoquant la formation très rapide des ions complexes. On s'est rapproché de l'obtention de bonnes formes d'anneaux en accélérant le processus de dissolution de l'Ag I dans la gélatine en l'alcalinisant très fortement et en élevant la température de la préparation: on a dissous dans de la gélatine une certaine quantité de cyanure de potassium. Il est en outre nécessaire de traiter la gélatine de façon appropriée pour éviter sa désagrégation.

Une autre possibilité de déceler les particules de Ag I est la capture des particules mêmes sur une couche de gélatine sans sel. Après la réduction appropriée des germes d'argent des particules au moyen de la lumière, il est possible de provoquer le développement physique qui consiste dans le dépôt autour des germes mêmes de particules d'argent provenant de la réduction d'un sel d'argent soluble. Il s'agit en substance de soumettre la plaquette à un bain révélateur pour le développement physique, consistant en la solution d'un sel d'Ag additionné à un réducteur. Ce prodédé est peu pratique parce qu'il est long et laborieux. Une méthode pour déceler les particules d'Ag I que je crois susceptible, une fois perfectionnée, de donner de bons résultats, est de provoquer, autour des particules dans la gélatine, le dépôt de copulants insolubles selon le principe énoncé ci-dessus sur l'action des formateurs.

Dans ce cas on n'obtiendrait pas de petits anneaux mais des petites taches colorées. Il s'agit en définitive d'amplifier l'action d'oxydation du germe de l'Ag jusqu'à en obtenir un rendement en couleur comparable à celui d'une particule des millions de fois plus grande. Ceci est possible grâce à l'action d'un dissolvant de l'Ag, tel que le ferri-cyanure de potassium et d'un autre sel qui reforme de nouveau de l'halogénure. Avec une technique appropriée, il est possible d'obtenir une production continue d'un colorant insoluble. Quelques essais effectués ont donné des résultats satisfaisants et ont démontré que cette façon de procéder était possible, mais la grande diversité des résultats obtenus

(essais positifs et essais entièrement négatifs) me font penser que les conditions de travail sont très délicates. D'autre part la difficulté de l'étude théorique des procédés de la chimie photographique ne m'ont pas permis d'évaluer quels sont les éléments à prendre en considération pour obtenir un résultat constant.

Une autre méthode susceptible de développement pour la détection des particules d'Ag I est de fixer les particules mêmes sur un verre de quartz, sur lequel on dépose du borax très fin ou du sel de phosphore. Sous l'action d'une flamme (soit réductrice, soit oxydante) l'Ag I réagit avec le sel, formant de très petites gouttelettes colorées en rouge. Par les essais effectués jusqu'à présent avec cette méthode, on ne peut obtenir que des valeurs indicatives sur les aérosols contenant des particules d'Ag I, parce qu'il n'est pas possible de déterminer la concentration des particules elles-mêmes, car les gouttelettes se colorent en rouge par la présence d'Ag I, mais ne permettent pas d'évaluer le nombre de particules ayant provoqué cette coloration.

Je suis convaincu qu'une étude approfondie de cette question, effectuée par des personnes bien au courant des difficultés de la recherche chimique, pourrait donner des résultats remarquables pour le perfectionnement des techniques d'insémination et pour le contrôle des précipitations provoquées.

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(Observatoire du Puy de Dôme, Clermont-Ferrand.)

Résultats préliminaires d'une étude expérimentale des noyaux glaçogènes naturels.

Par

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Avec 3 figures.

Résumé. Certains noyaux de congélation naturels ont été isolés. En effet, il a été trouvé, parmi les résidus de cristaux de glace produits au laboratoire dans de l'air naturel des particules douées d'activité glaçogène à une température de —12 à —15°. Leur nombre, sur les lieux et au moment des expériences, était de l'ordre de 1 par litre d'air. Ces noyaux n'ont pas une forme déterminée et ne présentent pas un faciès cristallin. Leur diamètre moyen varie généralement entre 7 et 25 microns. Ils paraissent constitués d'une partie insoluble et d'une partie hygroscopique et agir comme noyaux de congélation après avoir fixé de l'eau à l'état liquide. Enfin leur activité glaçogène n'est pas constante. Après avoir produit plusieurs fois un cristal de glace à environ —15° ils restent inactifs à —20°.

Zusammenfassung. Es wurde eine gewisse Art von natürlichen Gefrierkernen abgesondert. In den Rückständen von im Laboratorium aus natürlicher Luft erzeugten Eiskristallen wurden Partikel gefunden, welche die Fähigkeit hatten, bei Temperaturen von —12 bis —15° Eisbildung auszulösen. Bei den durchgeführten Experimenten betrug ihre Anzahl etwa 1 pro Liter. Diese Partikel haben keine besondere Form und erscheinen nicht kristallisiert. Ihre Durchmesser bewegen sich im allgemeinen zwischen Größen von 7 bis 25 μ. Sie erscheinen aus einem unlöslichen und einem hygroskopischen Teil aufgebaut und fungieren als Gefrierkerne, nachdem sich flüssiges Wasser an ihnen niedergeschlagen hat. Ihre eisbildende Aktivität ist nicht gleichbleibend. Nach der einige Male wiederholten Produktion eines Eiskristalles bei —15° blieben sie auch bei —20° inaktiv.

Summary. Certain natural freezing nuclei have been isolated. Among the residues of ice crystals produced in the laboratory in natural air, particles with activity for forming ice at temperatures ranging from —12° to —15° have been found. Their number, in the places and at the moments of our experiments were about 1 per liter. These nuclei have no particular shape and present no cristalline aspect. Their average diameter generally varies between 7 and 25 microns. They appear to be composed of an insoluble part and a hygroscopic part, and act as freezing nuclei after having fixed water in the liquid state. Their activity for forming ice is not constant. After having produced an ice crystal several times at about —15°, they remain inactive at — 20°.

Des observations effectuées en avion et des études photogrammétriques ont montré que des cristaux de glace apparaissent dans les nuages surfondus lorsque leur température atteint une valeur de —12 à —16°C. Ces cristaux peuvent être dûs à la congélation spontanée de grosses gouttes surfondues (LAFARGUE, 1953) ou bien produits par des noyaux glaçogènes.

L'existence de tels noyaux a été supposée par de nombreux physiciens et WEICKMANN (1949), KUMAI (1951), OKITA (1952) ont effectivement trouvé dans des cristaux de glace naturels des particules solides pouvant être leur noyau. WEICKMANN s'est préoccupé de l'activité glaçogène de ces particules mais il a borné son étude à celles trouvées dans des cristaux de glace provenant de cirrus. Il a constaté qu'elles agissaient comme noyaux de congélation à une température de —37°C.

Nous avons pour notre part (SOULAGE, 1954) examiné les résidus de cristaux de glace produits au laboratoire dans de l'air naturel à une température de —10 à —18°C et nous avons éprouvé leur activité glaçogène.

Ces résidus sont de trois types:

— type I: des résidus solides,

— type II: des résidus se comportant comme des noyaux gouttelettes de H. DESSENS (1946),

— type III: des résidus invisibles dans nos conditions expérimentales et dont l'existence est par suite hypothétique. S'ils existent, leur diamètre est inférieur à 1 micron.

Les résidus des types II et III placés dans une atmosphère saturée par rapport à l'eau et à une température aussi basse que —21° ne manifestent aucune aptitude à provoquer la congélation de gouttes d'eau ou à fixer directement la vapeur d'eau à l'état solide.

Par contre certains résidus du type I (27 sur 60 recueillis au cours de 150 expériences) placés dans les mêmes conditions d'humidité produisent un cristal de glace pour une température inférieure à une température critique.

Nous examinerons plus loin le cas des noyaux des types II, III et des noyaux du type I inactifs. Quant aux noyaux du type I actifs nous pouvons affirmer déjà qu'ils constituent une variété de noyaux glaçogènes. Nous avons précisé quelques-unes de leurs propriétés.

Leur nombre est en moyenne de l'ordre de 1 par litre d'air. Des précautions ont été prises afin que la chambre froide utilisée pour les recueillir (SOULAGE, 1953) n'introduise pas de noyaux: le refroidissement est produit par la fusion d'un mélange eutectique de glace et d'un sel; toute contamination de la chambre à nuages par le mélange est empêchée; un manchon de carton réchauffé entre chaque expérience et placé contre les parois évite la nucléation du nuage par leur givre; les lames de verre sur lesquelles les cristaux de glace sont recueillis sont soigneusement nettoyées avant leur utilisation. Elles sont lavées au mélange sulfochromique, puis à l'eau distillée et enfin séchées avec du papier joseph. Ainsi les noyaux recueillis se trouvaient bien dans l'air autour de l'appareil avant leur captation. Mais, toutes les expériences ont été effectuées à l'intérieur de bâtiments. Bien que ceux-ci aient été réservés à

notre travail et aient été soigneusement aérés avant chaque expérience nous ne pouvons affirmer qu'ils ne produisaient pas des noyaux glaçogènes. D'autre part les expériences ont été effectuées au sommet du Puy de Dôme et à Clermont-Ferrand. Les habitations, les usines de cette ville pouvaient elles aussi produire des noyaux.

Ces noyaux (fig. 1) n'ont pas une forme déterminée et ne présentent pas de faciès cristallin. Leur diamètre moyen varie généralement entre 7 et 25 microns, mais atteint pour certains 50 et même 80 microns. Ces dimensions sont supérieures à celles trouvées par WEICKMANN, KUMAI, OKITA pour les résidus de cristaux de glace naturels. WEICKMANN a observé des particules de 1 micron dans des cristaux de cirrus, KUMAI et

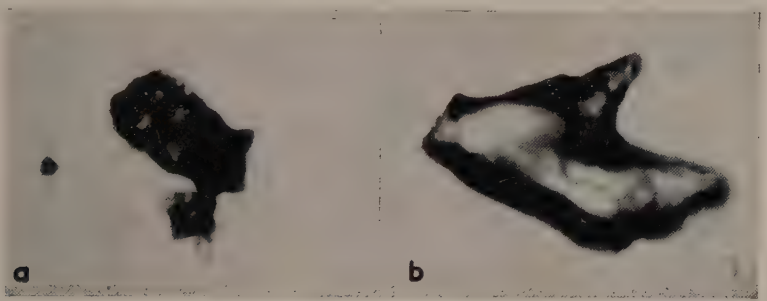

Fig. 1. Noyaux de congélation naturels actifs: (a) à —15°, (b) à —12°. Aggrandissement 1250 x.

OKITA respectivement des particules de 0,5 à 8 microns et moins de 0,5 à 14 microns dans des cristaux de glace précipitant jusqu'au sol. Des noyaux de 10 microns de diamètre ont une vitesse limite de chute de l'ordre du centimètre à la seconde. On peut se demander s'il leur est possible d'atteindre une altitude qui leur permette de jouer un rôle dans la formation des précipitations. Mais OKITA, se posant une question semblable rapporte que CROZIER et SEELY ont observé, par mètre cube, à 2.500 mètres d'altitude, 10.000 particules ayant un diamètre de 14 à 30 microns.

Après le nombre, la forme et la grosseur, le mode d'action et l'activité glaçogène des noyaux ont été étudiés. La technique suivante a été utilisée. Les noyaux sont disposés sous un microscope installé dans une cuve frigorifique. Un thermomètre à mercure et un thermocouple donne la température à leur voisinage. Un dispositif «reflex» permet d'observer et de filmer l'action des noyaux. On souffle légèrement autour du microscope. Les noyaux se trouvent dans un nuage surfondu et, pour une température inférieure ou égale à leur température critique d'action, produisent un cristal de glace.

En observant le phénomène nous avons constaté qu'un cristal de glace croissait sur certains noyaux sans que nous ayons pu déceler auparavant une modification appréciable de leur aspect (fig. 2). Nous pensons cependant que ces noyaux sont des noyaux de congélation et non de sublimation et ceci pour trois raisons:

D'abord, répétant les expériences nous avons parfois décelé avant l'apparition de la glace une augmentation de la brillance des noyaux explicable par la formation à leur surface d'un film d'eau.

Ensuite, ces mêmes noyaux et tous les autres placés dans une goutte d'eau qu'ils ont rencontrée ou condensée provoquent sa congélation à leur température critique (fig. G. SOULAGE, 1954).

Fig. 2. Action glaçogène du noyau (a) de la figure 1 après désagrégation partielle au cours des expériences postérieures au cliché de la figure 1. (1), le noyau avant l'humidification; (2), le noyau est humidifié depuis 25 secondes: il ne paraît pas sensiblement mouillé; (3), 1 seconde après le cliché (2) le noyau agit; (4) et (5), 1 et 5 secondes plus tard la glace progresse; (6: grossissement 4,3 fois moindre que pour les clichés précédents), le cristal de glace produit par le noyau 5 minutes environ après le début de sa formation.

Enfin ils paraissent partiellement hygroscopiques. Ils sont capables de condenser une quantité importante d'eau (fig. 3), sans s'y dissoudre subtantiellement, pour un degré hygrométrique de l'air compris entre 90 et 100. S'ils étaient absolument insolubles ils pourraient peut-être,

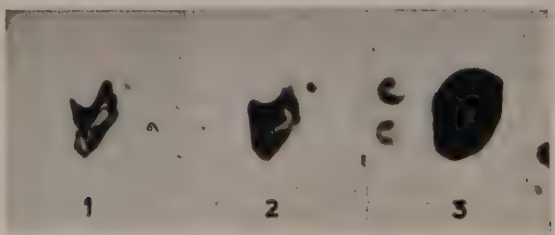

Fig. 3. Hygroscopicité du noyau b de la figure 1. (1), noyau sec; (2), le noyau à 93% d'humidité, (3). le noyau à 97% d'humidité.

à cette humidité, fixer un film d'eau mais ils ne pourraient pas condenser une goutte d'eau. Ce n'est, en effet, que dans une atmosphère sursaturé par rapport à l'eau qu'un corps insoluble peut agir comme noyau de condensation suivant le processus indiqué par OGIWARA (1950) et développé récemment par DUFOUR et DEFAY (1954).

Les noyaux étudiés paraissent ainsi être des noyaux de congélation et comprendre, à côté d'un corps solide et insoluble, un corps hygrosco-

pique. Une observation de JUNGE (1952) constatant qu'il existe dans l'atmosphère très peu de particules entièrement insolubles fournit un appui supplémentaire à cette dernière hypothèse. Quant à l'insolubilité, au moins partielle, des noyaux de congélation naturels, elle a déjà été supposée par RAU, SCHULZ, DORSEY (voir MASON et LUDLAM, 1951) et MASON (1953).

Pour déterminer la température critique d'action des noyaux nous les avons humidifiés à des températures décroissantes jusqu'à ce qu'ils produisent un cristal de glace. Nous avons constaté qu'ils ne présentaient pas une activité glaçogène constante et que cette activité ne variait pas de la même façon pour tous. La grande majorité des noyaux (23/27), après avoir de 5 à 10 fois produit un cristal de glace à une même température critique de l'ordre de —12 à —15°, a montré une activité irrégulière et décroissante et a ensuite cessé de manifester toute activité à une température aussi basse que —20°. Un petit nombre par contre (4/27) s'est montré inactif après avoir une seule fois agi sous nos yeux à une température de —12 à —15°C. Cette dernière observation est importante. Elle nous permet de formuler l'hypothèse que les résidus des divers types trouvés inactifs constituent ou du moins contiennent eux aussi un noyau glaçogène mais qui a été désactivé par un premier et seul fonctionnement.

Pour conclure je rappellerai que les noyaux d'iodure d'argent et divers noyaux artificiels manifestent également une activité glaçogène variable (SOULAGE, 1953; PICCA, 1954). A côté de l'intérêt immédiat que présente une étude de leur désactivation pour les essais de pluie provoquée ou de prévention de la grêle, cette étude peut apporter des précisions et des suggestions intéressantes sur les processus d'action et de désactivation des noyaux naturels.

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Giant Hygroscopic Nuclei in the Atmosphere and their Role in the Formation of Rain and Hail.

By

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With 1 Figure.

Summary. The results of two years' observations of the hygroscopic particle content of the surface air at five places in West Pakistan show that sea-salt particles of mass up to 10^{-9} gram may penetrate far into the interior of continents. Larger particles appear rather more numerous inland than would be expected if their sole source is the ocean, and some other possible sources are discussed. The observed particle concentrations in the Punjab suggest that the fragmentation of large droplets may play an important part in the formation of heavy rain in this area.

Zusammenfassung. Die Ergebnisse von zweijährigen Beobachtungen des Gehaltes der bodennahen Luft an hygroskopischen Teilchen an fünf verschiedenen Stellen in Westpakistan zeigen, daß Salzteilchen aus dem Meerwasser bis zu einer Masse von 10^{-9} Gramm weit in das Innere des Kontinents getragen werden können. Auch größere Teilchen werden dort in größerer Zahl angetroffen, als man erwarten würde, wenn sie ausschließlich vom Ozean kämen. Einige Möglichkeiten einer anderen Herkunft werden diskutiert. Die beobachteten Partikel-Konzentrationen im Punjab deuten darauf hin, daß die Zerteilung großer Tröpfchen bei der Entstehung starker Regenfälle in diesem Gebiet eine bedeutende Rolle spielen könnte.

Résumé. Des prélèvements de particules hygroscopiques dans la basse atmosphère ont été faits deux fois par semaine pendant deux années dans le Pakistan occidental. Il en ressort que des noyaux de sel marin dont la masse s'élève jusqu'à 10^{-9} grammes pénètrent souvent à l'intérieur des continents. Pour expliquer la présence très loin de la mer de particules encore plus grosses on est amené à leur attribuer une autre origine. La faible teneur en noyaux géants de l'air du Punjab nous fait penser que le processus de multiplication de gouttelettes par éclatement des plus grosses joue un rôle important dans la formation des fortes pluies observées dans cette région.

I. Introduction.

Though the study of airborne condensation nuclei dates from the pioneer work of AITKEN at the close of the last century, attention has

only recently been paid to the larger hygroscopic particles which may play an essential role in the formation of rain.

Interest in large hygroscopic nuclei (i. e., those of mass greater 10^{-12} gram) was stimulated largely by Langmuir's (1948) theory of multiplication of raindrops by a "chain reaction" and by Ludlam's (1950, 1951) work on the production of raindrops by the coalescence of cloud droplets. These theories require the presence in "warm" clouds of some rare droplets of 40 microns or more diameter, that is to say well outside the size spectrum of the great majority of cloud droplets.

That hygroscopic particles large enough to produce droplets of this size are in fact to be found in the atmosphere was first demonstrated by Dessens (1946). Since then a great deal of work has been done (Woodcock and Gifford, 1949; Fournier d'Albe, 1951; Woodcock, 1952, 1953; Moore, 1952) on the numbers and size distribution of the hygroscopic particles present in maritime air. The main sources of the particles seem to be waves breaking on the coasts and on the open sea in winds exceeding 15 knots; the bursting of bubbles on the sea surface has also been shown (Aliverti, 1950; Facy, 1951, et al.) to produce appreciable numbers of particles of a wide size range.

As maritime air moves inland towards the interior of continents the salt particle concentration may be expected to decrease, partly by fall to the ground under gravity and partly by "raining out". The experimental work in Pakistan which will be described here was undertaken in order to throw some light on the transport of particles inland. In particular, a knowledge of the natural concentration of large salt particles was considered essential in planning experiments in cloud-seeding with artificial salt particles, which can only be expected to produce measurable effects if they outnumber, locally at least, the natural particles.

II. The Distribution of Salt Particles in West Pakistan.

A. Sampling Technique.

For two years, from May 1952 to May 1954, regular samples of the salt particle content of the surface air were taken twice weekly at five stations in West Pakistan by personnel of the Pakistan Meteorological Service. One of these stations (Karachi) lies on the coast of the Arabian Sea, while Peshawar lies over 1000 km. from the coast, One station (Quetta) is at a height of 1700 m. above sea level.

The instruments used for sampling, known as Cascade Impactors, have been fully described by May (1945). These have the advantages of simplicity and cheapness and of being able to take samples from large volumes of air. They have been used successfully by regular meteorological observers, after a short period of training, without interruption of their normal duties.

The suspended matter in the volume of air sampled is deposited on four glass slides, which are enclosed for examination by microscope in a chamber in which the relative humidity is controlled by the presence of a salt solution of known concentration. The hygroscopic particles then grow into droplets on the slide and their diameters are measured with the aid of a special graticule. Details of this method of sampling and counting have been published elsewhere (FOURNIER D'ALBE and LATEEF, 1953).

The volume of air sampled was varied from station to station and from season to season in order to sample the greatest possible volume of air while avoiding overcrowding of particles on the slides. In counting the particles, no attention was paid to those forming droplets of less than 2 microns radius in equilibrium with a 10% solution of NaCl. and thus containing less than 3×10^{-12} grams of salt. In order to obtain samples as representative as possible of the lower atmosphere, they were taken invariably in the afternoon, at a time when convectional and turbulent mixing is at a maximum.

B. Size Distribution of Particles and Seasonal Fluctuations.

In Figure 1 are shown the size distribution of the airborne salt particles captured at the five stations in West Pakistan.

The curves for Karachi, except that for the winter season when the wind blows off the land, are generally of the same form as those obtained by WOODCOCK and MOORE at moderate wind speeds over the open sea. During the summer and monsoon seasons the wind over the northern Arabian Sea is moderate to fresh and it is probable that the majority of the salt particles are formed in the open sea rather than by breakers on the coast.

At Hyderabad the monsoon change is very marked both in summer and autumn. With the incursion of maritime air, the concentration in all size groups increases by factor of nearly 100, while at the same time the slope of the curve becomes slightly steeper.

Further inland, at Lahore and Peshawar, the changes are less well-marked, but nevertheless the influx of the south-west monsoon current is often clearly reflected in the values of salt-particle concentration. At Quetta the seasonal variation is hardly significant, since the monsoon airstream seldom reaches there. The outstanding feature of the salt particle concentration at Quetta, which is also observed though less clearly at Karachi and Hyderabad, is its high correlation with dew-point temperature. The probable reason for this is that Quetta is surrounded in all directions by desert for hundreds of miles, and the main source both of water vapour and salt particles in the air at Quetta is the Arbian Sea. The correlation between salt particle concentration and dew-point is not observed either at Lahore or Peshawar, where evapo-transpiration supplies water vapour but no salt particles to the surface air.

III. Transport of Particles.

No direct attempt was made during these experiments to determine the chemical nature of the hygroscopic particles, since this was not thought essential to their behaviour as centres of condensation. The higher concentrations observed at Karachi and Hyderabad permit us to assume that at these stations near the coast the particles captured consist mainly of sea-salt. The question arises as to whether the particles captured as far as 1000 km. inland are also sea-salt or whether they are of different origin.

Apart from the sea one may imagine as sources of large hygroscopic (a) combustion processes, both domestic and industrial; (b) salt deserts and other land surfaces where salt lies exposed on the ground and liable to be blown up by the wind; and (c) the evaporation of falling raindrops.

As far as West Pakistan is concerned we may discount source (a) except in the immediate neighbourhood of salt mines. There is very little industry in the country and the climate does not encourage the burning of domestic fires, except for cooking.

There is no evidence that large numbers of salt particles are raised by the wind from desert surfaces. Quetta in summer often experiences thick dust haze from the deserts to the west, where there are large areas of salt waste, but no significant rise in hygroscopic particle concentration has been observed on these occasions. It is possible that the salt lies on the surface in the form of large grains which, though raised by strong winds, rapidly fall out again under gravity.

In arid regions rain is commonly observed to fall from clouds but to evaporate before reaching the ground. As each raindrop may be expected to contain the aggregated nuclei of thousands of cloud droplets, this mechanism may be a source of large particles, but one whose importance is very difficult to assess. Some observations have been made with the cascade impactor during and after heavy rain: there is usually a sharp decrease in number of the smaller particles (mass less than 10^{-9} g.) but a slight increase in number of the larger ones. These measurements were made in conditions where relatively few raindrops can have evaporated during fall, and they cannot be taken as a basis for a quantitative argument. It seems unlikely that on a continental scale the evaporation of raindrops is comparable in importance to the ocean as a source of large particles. On a local scale, however, it may be of significance, since it provides a mechanism whereby one raincloud can in some circumstances "seed" its neighbours. The process, however, is not confined to rainclouds. Even fair-weather cumulus may provide the conditions in which large hygroscopic particles may increase their size by coalescence without actually producing rain. One might expect to find, for instance, an unusally high concentration of large nuclei at cloud level after the dispersion of small cumulus or thick stratocumulus cloud.

In general, it may be expected that rain will remove rather than add to the hygroscopic particles in the atmosphere. The other main

removal mechanism is undoubtedly sinking of the particles under gravity.

The rate of loss by fall to the ground may be expressed by the equation

$$C = C_o \exp\ (-vt/h), \qquad (1)$$

where C_o is the concentration at time $t=0$ of particles whose terminal velocity of fall is v, assuming that the lower atmosphere is mixed up to a height h above the ground. This condition may be approached during daytime in fine weather and may even persist during the night except in the layers near the ground.

If v is expressed in centimetres per second and h in kilometres, then the time (t) for the concentration of particles of any size to fall by a factor of 2 is given by

$$t = 19.25\, h/v \text{ hours.}$$

In the following Table is shown the "half-life" of particles of various masses on various assumptions as to the mixing height. The terminal velocities of the particles, calculated from modified Stokes Law, have been assumed equal to those of spheres of mass equal to the particles and of the density of dry salt.

Table 1. *"Half-life" of airborne particles.*

Mixing height	Mass of particles (grams)			
	10^{-11}	10^{-10}	10^{-9}	10^{-8}
1 km.	45 days	10 days	50 hours	11 hours
2 km.	90 days	19 days	101 hours	22 hours
5 km.	225 days	49 days	252 hours	54 hours

One may apply this rough analysis to the actual concentrations observed in Pakistan. The sampling station at Karachi lies very close to the coast, and for a better estimate of the initial concentration of salt particles in air moving inland one may take the values observed at Hyderabad. This station is separated from the sea by a hundred miles of hot desert and in daytime the maritime air can be assumed to be fairly well mixed up the level of the inversion (between 1 and 2 km.) by the time it reaches Hyderabad. From the concentrations observed there, by assuming a plausible wind speed and trajectory, one may calculate the losses through gravity fall between Hyderabad and Lahore or Peshawar.

It appears that the hygroscopic particles containing 10^{-9} grams of salt or less which are captured at Lahore and Peshawar may well have been seasalt transported from the Arabian Sea or even the Bay of Bengal. Particles heavier than 10^{-9} grams are not likely to penetrate more than a few hundred miles inland and those occasionally found at Lahore and Peshawar may be of local origin, perhaps from the grinding and use of domestic salt, but more probably from the evaporation of rain or of large cloud droplets.

The concentrations of the smaller particles at Lahore and Peshawar are much lower than would be expected merely from consideration of the losses in transport. Rain is certainly responsible for the removal of large numbers of particles, as is shown by the low concentrations observed during and after showers. Another cause of the low concentrations at Lahore and Peshawar may be mixing of the monsoon airstream on its journey from the coast with continental air from Baluchistan and Afghanistan. The particle content of the air at Quetta remains low throughout the year except on the rare occasions when the monsoon invades the Baluchistan plateau.

IV. The Role of Salt Particles in Rain Formation.

The production of rain by the coalescence of cloud droplets has been discussed by various authors, notably Ludlam (1951) and Woodcock (1952). Ludlam has shown that a salt particle entering a cloud may be expected to grow to a diameter of about 40 microns within 30 seconds, provided that it contains more than 10^{-9} grams of salt. We may, as a rough guide, take the latter figure as the lower mass limit of the particles which may become effective precipitation elements in cumulus type clouds.

Reference to Figure 1 shows that in the Punjab (Lahore) the average concentration of particles of mass greater than 10^{-9} gram in the surface air is of the order of 10 per cubic metre during the monsoon season. If we assume, as an extreme case, that this concentration does not decrease with height but remains constant up to 10 km.; and that all particles of mass greater than 10^{-9} gram in a column of air of this height are precipitated as raindrops of 4 mm diameter, then the amount of rain will be 3.2 mm.

Alternatively one may consider an isolated cumulus cell of horizontal radius 1 km. and updraught 5 m./s. During a lifetime of 2000 secs., a volume of air of $10\,\pi$ km^3 enters the base of the cell, carrying $\pi \times 10^{11}$ large particles. If each of these grows to a raindrop of 4 mm. diameter, the volume of water precipitated is 1.1×10^{10} ccs., or enough for 1 mm. of rain over 11 km^2.

The fact that such rainfall amounts are exceeded in the Punjab almost every time that rain falls during the monsoon season leads us to suppose either that the number of "rainmaking" particles is much larger than supposed (i. e. that the critical mass is much lower), or that droplet multiplication by the break-up of large drops is a common feature of shower clouds in this region.

The possibility of the ice phase intervening in the rain-forming process may be virtually ruled out. During the monsoon season in the Punjab the temperature at cloud base is between 20° and 25°C, and there is no doubt that most of the rain falls from clouds whose summits do not reach even the 0°C isotherm, which is at about 6 km. above cloud base.

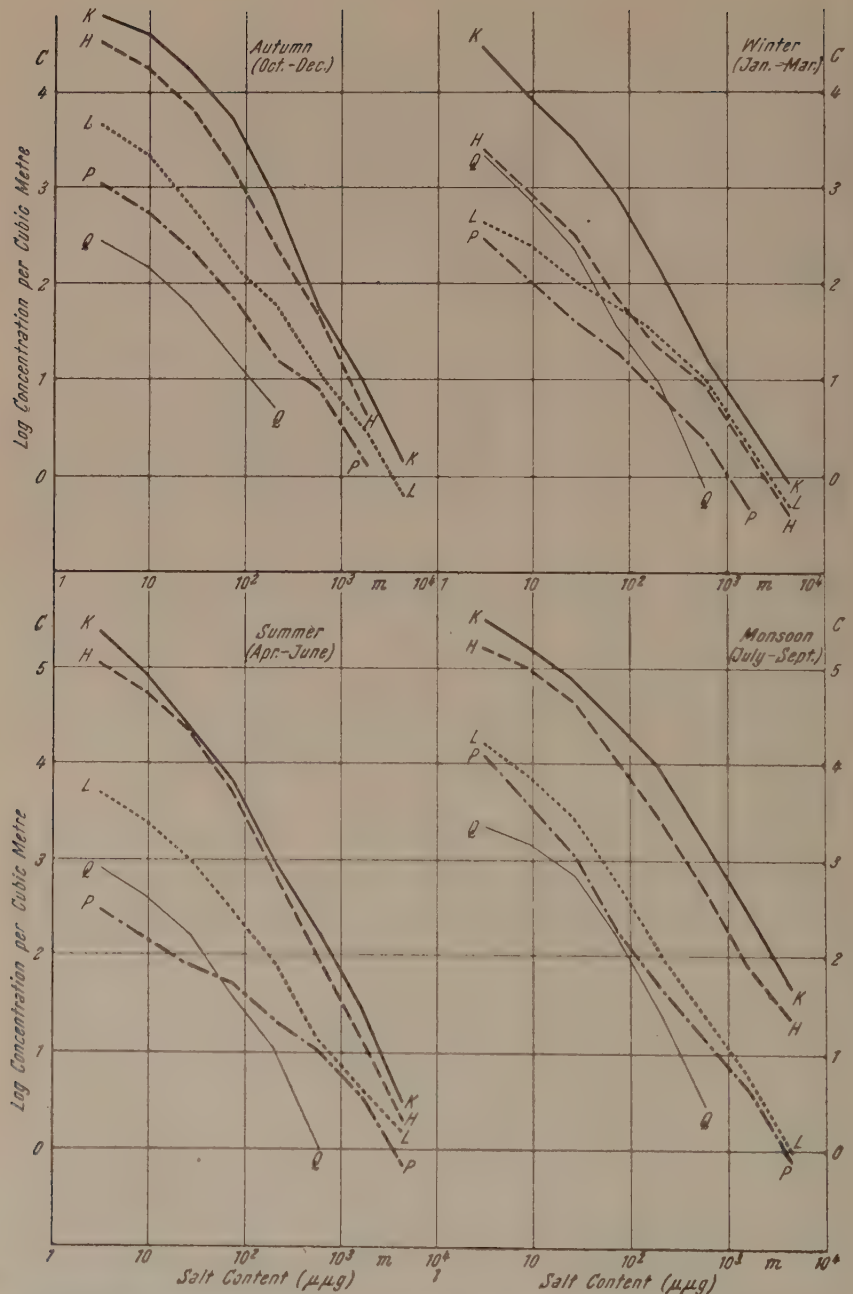

Fig. 1. Size distribution curves of hygroscopic particles at Karachi, Hyderabad, Lahore, Peshawar and Quetta.

The break-up of large water droplets during fall has been investigated by LENARD (1904) and BLANCHARD (1948), though neither of these authors studied particulary the number and size distribution. FOURNIER D'ALBE and HIDAYETULLA (paper in preparation) have studied the fragmentation of large drops falling free air, by catching the fragments on filter paper and employing the technique of measurement used in the study of raindrop size distributions. Several hundred drops of diameter between 8 and 12 mm. were observed.

It was noticed that during a fall of 20 metres in calm air only drops of 9 mm. diameter or more invariably broke up. Smaller drops would break up only in conditions of natural or artificially induced turbulence. It has been generally assumed that drops become unstable at 5—7 mm. diameter, and this is certainly the case in turbulent air. The probability of break-up may be proportional to the distance fallen, and it is likely that in natural conditions of free fall through great heights the limiting diameter is nearer 5 than 9 mm. The largest raindrops so far recorded had diameters between 6 and 7 mm. In the absence of collisions between large drops, it seems safe to take for the purposes of argument 7 mm. as the limiting diameter.

The growth of the fragments produced by the break up of a large drop in cloud is governed by the relations:

$$4\pi r^2 \cdot dr = \pi r^2 \cdot Em \cdot dz \tag{2}$$

$$4\pi r^2 \cdot dr = \pi r^2 \cdot Emr \cdot dt \tag{3}$$

where r is the droplet radius, v its terminal velocity, m the liquid water content of the cloud and E the collection efficiency, which may be taken as approximately equal to 0.9.

As will be seen later, the majority of fragments produced on break-up have diameters greater than 1 mm. In the following Table are shown the times necessary for the growth to 7 mm. by coalescence of drops of various sizes in an ideal cloud containing 2 grams of liquid water per cubic metre. Also shown are the distances fallen in still air during this time and the distance relative to the ground in a steady updraught of 5 m./s.

Table 2. *Growth of droplet fragments.*

Diameter of fragment (mm.)	1	2	3	4	5
Time to grow to 7 mm. diam. (sec.)..	790	595	455	335	220
Distance fallen in still air (m.)	6600	5500	4400	3300	2200
Distance fallen in updraught of 5m./s. (m.)	2650	2525	2125	1635	1100

The average number and size distribution of the fragments produced by the break-up of drops of 9—10 mm. diameter are shown in Table 3.

Table 3. *Number of fragments produced by the break-up of 10 drops of diameter 9—10 mm.*

Range of fragment diameter (mm.).	1	1—2	2—3	3—4	4—5	5—6	6—7	7—8	Total
Number of fragments	32	89	57	26	10	14	7	3	238

The form of the size distribution curve of the fragments produced by the break-up of even larger drops (up to 12 mm. diameter) is very similar, though the average number of fragments produced increases from 24 in the size range 9—10 mm. to 29 in the 10—11 mm range, and to 34 in the 11—12 mm. range.

Extrapolation of these results to parent drop sizes of 7 mm. is a risky undertaking, but as a rough estimate we may assume that the break-up of a drop of 7 mm. diameter produces on the average 15 fragments, of which the majority have diameters between 1 and 4 mm.

V. Conditions for Multiple Fragmentation.

LUDLAM (1951) has shown that the maximum diameter to which droplets can grow by coalescence in a cloud of unlimited depth is a function only of the velocity of the updraught. An updraught of approximately 4 m./s. is sufficient for the growth of droplets from 40 microns to 7 mm. diameter. The time required for this growth is of the order of 25 minutes (1500 secs.), and is less the larger the initial diameter.

From Table 2 it appears that if repeated fragmentation is to take place, the break-up of the parent droplets must occur at least 1500—2000 metres above the base of a cloud in which the updraught is 5 m./s. The height above cloud base at which fragmentation commences will be approximately equal to 1500 (U—4) metres, where U is the velocity of the updraught in metres per second. Thus if the updraught exceeds 5.5 m./s. the conditions for multiple fragmentation may be satisfied. This velocity of updraught is quite critical, since the vertical thickness of cloud required by the fragments for growth to 7 mm. diameter decreases rapidly with increasing velocity of updraught.

Once multiple fragmentation starts it proceeds very rapidly. In the case of an updraught of 5.5 m. s., the smallest fragments (i. e. 1—2 mm. diameter) will remain suspended at about the same level, since this is approximately their terminal velocity. The larger drops will fall through the cloud and rain will begin to fall from the base of the cloud approximately 500 seconds after fragmentation commences at 2200 metres above cloud base. At this level, there will be a rapid accumulation of small raindrops which will eventually filter out an increasing proportion of the cloud droplets from the rising air current, will starve the upper parts of the cloud of liquid water, and by their accumulated weight eventually suppress the updraught.

In stronger updraughts the formation of heavy rain by fragmentation will spread upward as well as downward through the cloud, from the level at which fragmentation first occurs.

A computation of the rate of increase in the number of large droplets by the fragmentation process shows that by about 10—15 minutes after it commences the rate of production of raindrops by fragmentation may exceed the rate of production by the ordinary process of coalescence on large nuclei (given the nucleus concentrations observed in the Punjab).

VI. Concluding Discussion.

We may distinguish three phases in the development of heavy rain in "warm" convective type clouds: condensation, coalescence and fragmentation.

A. Condensation.

The first phase is the production of the cloud by condensation of water vapour. In cumulus clouds the droplets may initially be as numerous at 1000/cc, or 10^9 per cubic metre, and of diameters ranging from 2 to 15 microns. Probably every hygroscopic particle of mass greater than 10^{-15} gram takes part in this condensation and also some of the larger insoluble particles.

The vast majority of the cloud droplets thus formed play essentially a passive role in the formation of rain. They provide the environment in which the processes of coalescence and fragmentation may later evolve. If the cloud extends high above the 0°C isotherm some of the cloud droplets may freeze. Even these, in clouds whose base temperatures exceed 10°C, continue to play only a secondary role. Their freezing merely represents a change in the environment of the "coagulation elements" formed on the large hygroscopic particles.

During the first minute in the life of the cloud, a small number of droplets, those that have condensed on to hygroscopic particles containing more than $.10^{-9}$ grams of salt, will grow to diameters of the order of 40 microns. Their number will depend on the concentration of giant hygroscopic particles in the air entering the cloud base. In maritime air this may be of the order of $100/m^3$; inland it appears to fall off very roughly by a factor of about 10 for every 1000 km. of trajectory from the coast, though wide variations in concentration may be expected.

B. Coalescence.

Coalescence with cloud droplets becomes comparable in importance to condensation by the time the giant hygroscopic nuclei have grown to a diameter of 40 microns, and is the predominating factor in growth beyond 100 microns.

The size to which these large droplets can eventually grow is deter-

mined primarily by the macrophysical properties of the cloud, such as vertical depth, liquid water content and updraught velocity, and only secondarily by the numbers and size distribution of the main cloud population.

This aspect of the problem has been thoroughly investigated by Ludlam, who also drew attention to the fact that in its growth to raindrop size, a droplet sweeps several litres of air, which may contain frozen particles if its trajectory takes it up to the neighbourhood of the —20°C isotherm. If the cloud has been seeded with silver iodide, the growing droplet is liable to encounter an ice particle near the —7°C isotherm. The freezing of a large droplet causes a decrease in its density and a slowing down of its growth; but it also introduces the possibility of it forming a hailstone. This possibility appears particularly likely in Europe during the summer, where an abundance of large hygroscopic particles may be expected in clouds whose base temperatures are in the neighbourhood of 10—15°C. Since the body of the cloud may be regarded as an environment determining the evolution and growth of the large hygroscopic particles, one may wonder whether seeding clouds in maritime air with freezing nuclei such as silver iodide does not tend to increase, rather than diminish, the chances of hail formation.

In general, maritime air contains sufficient large salt particles to account for the observed rates of rainfall by coalescence alone, without recourse to drop multiplication by break-up. Inland, as we have seen, this may not be the case.

C. Fragmentation.

We have seen that the observed rates of rainfall in the Punjab cannot be accounted for without either a) accepting that particles of salt content much less than 10^{-9} gram may grow into precipitation elements, or b) admitting the multiplication of raindrops by fragmentation.

The conditions for droplet growth to unstable size in clouds of base temperature 20°C appear to be: a vertical depth exceeding 4 km. and an updraught velocity exceeding 4 m. s. It has been shown that for multiple fragmentation the updraught should exceed this velocity by at least 1.5 m. s. There seems no reason to doubt that these conditions are frequently satisfied.

If the updraught velocity does not exceed 6—7 m. s. the fragmentation process may be limited to the lowest 3—4 km. of the cloud, where after a few minutes the rate of production of raindrops by fragmentation will predominate over that due to coalescence. In this case the upper parts of the cloud may cease to play a significant part in the production of heavy rain. With updraughts exceeding 7—8 m./s. the situation becomes very much more complicated, since fragmentation may spread to all parts of the cloud. It is not likely to extend far above the —10°C isotherm, however, since it ceases, or is at least greatly reduced, if the droplets become frozen.

D. Effect of Seeding with Artificial Nuclei.

On occasions when the conditions for multiple fragmentation are not satisfied, it seems reasonable to expect that an increase in the concentration of large hygroscopic particles entering the cloud may produce a comparable increase of the volume of rain formed. To produce a significant increase it is necessary that the artificial particles should be at least as numerous as the natural particles in the same size range, though a limit to the extra amount of rain produced will always be set by the macrophysical characteristics of the cloud system. It is unlikely that artificial nuclei would ever produce rain in a cloud which would otherwise give none, except in the extreme case of a total absence of large natural hygroscopic particles.

In clouds in which multiple fragmentation can occur, this process is likely to outweigh coalescence in the production of raindrops. In this case the advantage to be gained by increasing the large particle content of the air entering the cloud is less certain. It is likely to be effective only if the time during which fragmentation may continue is very limited, when the number of primary fragmentations per unit time may be important. This is perhaps often the case, since the life of individual cumulus cells rarely exceeds 15—20 minutes.

E. On the Need for Further Study of Giant Hygroscopic Nuclei.

According to LUDLAM, rain may develop by coalescence in clouds whose base temperature exceeds 10°C without the tops of the clouds rising above the 0°C isotherm. In many cases coalescence is likely to anticipate the BERGERON process in the formation of showers even if the cloud summits do contain some ice crystals.

From surface climatological data on temperature and relative humidity it is possible to estimate approximately the average temperature at cloud base. It has been shown for instance, that in summer the whole of Europe except northern Scandinavia lies to the south of the 10°C cloud base isotherm. This suggests that the coalescence process may be responsible for a greater proportion of the convective summer rain falling in Europe than is generally supposed. Little appears to be known however about the natural concentration of large hygroscopic particles in the air over Europe.

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(Etablissement d'Etudes et de Recherches Météorologiques, Magny-les-Hameaux.)

La capture des noyaux de condensation par chocs moléculaires au cours des processus de condensation.

Par

L. Facy.

Résumé. Les processus de transfert de vapeur autour d'une gouttelette en cours d'évaporation ou de condensation peuvent être observés optiquement en introduisant dans l'atmosphère un aérosol inerte de particules diffusantes submicroscopiques. L'examen sur fond noir, en éclairage latéral, permet de suivre ainsi la trajectoire et la vitesse des particules témoins sous l'action des chocs qu'elles reçoivent des molécules de vapeur d'eau se dirigeant ou s'éloignant de la goutte observée.

Le transfert de vapeur d'eau se matérialise par un déplacement continu, facilement mesurable, superposé au mouvement Brownien habituel des particules. L'observation d'une goutte en voie d'évaporation met en évidence une chemise noire de protection analogue au «dust free space» des phénomènes d'origine thermique. Une goutte en voie de condensation par contre visualise un mécanisme de cinétique moléculaire permettant la capture des particules submicroscopiques. Les conséquences de ce mécanisme de capture rendent facilement explicables certains processus de la microphysique des nuages. On peut en tirer des conclusions pratiques applicables à l'insémination des nuages par des aérosols à propriétés particulières ou pour le dépoussiérage rapide des locaux industriels et des mines.

Zusammenfassung. Der Dampftransport während der Verdunstung und Kondensation von Tropfen kann direkt optisch durch Einführung von Aerosolen zerstreuender, submikroskopischer Teilchen beobachtet werden. Seitenbeleuchtung gestattet, die Bahnen und Geschwindigkeiten, die diese Teilchen bei molekularen Zusammenstößen mit den sich zum Tröpfchen hin oder vom Tröpfchen weg bewegenden Wasserdampfmolekülen erhalten, zu verfolgen.

Der Wasserdampftransport besteht in einer steten, leicht meßbaren Partikelbewegung, welche sich der üblichen Brownschen Bewegung überlagert. Die Beobachtung eines verdunstenden Tröpfchens zeigt eine Art Schutzmantel, den „dust-free space", wie er von anderen thermischen Erscheinungen bekannt ist. Von einem kondensierenden Tröpfchen hingegen werden die submikroskopischen Partikel infolge molekularer Zusammenstöße eingefangen. Dieser Prozeß macht einige Vorgänge der Wolken-Mikrophysik verständlich. Daraus ableitbare Folgerungen können bei Operationen zur künstlichen Regenerzeugung oder zur Reinigung staubhaltiger Luft verwertet werden.

Summary, The process of vapor transfer during evaporation or condensation of droplets may be observed directly by introducing aerosols of diffusing submicroscopic particles. When lighted by a lateral beam, velocities and trajectories of these particles are visible under molecular collisions from vapor molecules reaching or leaving the droplet.

Vapor transfer materializes itself by a continuous, easily measurable displacement of the particles, superposed with the usual Brownian motion. A freely evaporating droplet is surrounded by a dust-free space similar to that observed in thermic repulsion. A condensing droplet, on the contrary, shows a process of capture due to molecular collisions of the submicroscopic particles.

This mechanism of molecular capture may explain some processes which occur in microphysics of clouds. These principles may be applied to artificial inducement of precipitation or for cleaning dusty air.

Depuis AITKEN, LODGE et CLARKE, l'attention avait été attirée sur le «dust free space» ou espace noir de protection entourant les corps chauffés et que l'on observe facilement sous éclairage latéral dans une atmosphère chargée de fumée.

Nous avons pensé que cet effet de bombardement moléculaire des particules en suspension pouvait se réaliser non seulement dans le cas d'un gradient thermique, mais aussi lorsqu'il existe un gradient de tension de vapeur d'un gaz étranger diffusant d'une zone source vers une zone puits dans une atmosphère isotherme au repos.

En utilisant les techniques habituelles d'étude d'un nuage particulaire dans une cellule d'examen où deux solutions de tensions de vapeur différentes permettent la réalisation de gradients prédéterminés, on observe avec la plus grande facilité le déplacement des particules en suspension sous l'effet du bombardement par les molécules de vapeur diffusant de la solution à tension de vapeur élevée vers la solution à tension de vapeur faible.

Des précautions très particulières doivent être prises pour éviter tout mouvement convectif dans la cellule d'examen: une intensité modérée de la source lumineuse utilisée et un choix judicieux du nuage particulaire permettent de s'affranchir des effets secondaires de photophorèse.

Les particules submicroscopiques en suspension dans l'atmosphère jouent alors le rôle d'indicateurs très sensibles et matérialisent dans un rapport cinétique simple l'afflux des molécules de vapeur diffusant de la source vers le puits. Le transfert de vapeur est ainsi rendu directement visible par le déplacement continu des particules: déplacement facilement mesurable, superposé au mouvement Brownien habituel dont les fluctuations demeurent encore perceptibles pour les faibles vitesses correspondant aux très petites différences de tension de vapeur.

Il est commode par exemple de réaliser la zone source et la zone puits, l'une par une gouttelette placée au centre du champ, l'autre par les parois cylindriques de la chambre d'examen, et de reproduire ainsi les conditions d'évapo-condensation d'une goutte dans une atmosphère où règne à l'infini une tension de vapeur déterminée.

Dans le cas d'études portant sur la diffusion de la vapeur d'eau, la

zone source est garnie d'eau distillée; les solutions à tension de vapeur plus faible peuvent être soit des dilutions connues d'acide sulfurique, soit des solutions saturées de sels. Dans tous les cas bien entendu la température de la chambre d'examen est relevée avec précision.

La goutte centrale est déposée sur un support mince, métallique ou en fil de verre; les parois sont recouvertes de buvard ou de tissu de verre et imprégnées de l'autre solution.

L'axe du microscope étant disposé horizontalement on peut examiner un plan vertical et observer le déplacement des particules dans une coupe méridienne. Les trajectoires et les vitesses varient du sommet au pôle inférieur de la goutte par suite de la composition du mouvement dû à l'action de la pesanteur et celui, radial, dû au gradient de tension de vapeur.

On peut plus commodément faire pivoter l'ensemble et, en rendant vertical l'axe du microscope, examiner alors le plan équatorial de la goutte. Dans ce cas on observe directement la composante radiale du mouvement de la particule sous l'action du seul bombardement moléculaire. La latitude de mise au point du microscope permet de suivre suffisamment la particule avant sa disparition, tout au moins pour les vitesses de chute faibles devant celles imposées par les effets cinétiques.

L'observation d'une goutte en voie d'évaporation met en évidence une chemise noire de protection analogue au «dust free space» d'origine thermique.

Une goutte en voie de condensation par contre visualise l'efficacité d'un processus de capture des particules submicroscopiques par un mécanisme de cinétique moléculaire pure.

On peut considérer que chaque particule, supposée sphérique, est soumise sur l'hémisphère faisant face aux tensions de vapeur élevées à un ensemble de percussions élémentaires de la part de n_1 molécules diffusant de la source vers le puits. Sur l'hémisphère faisant face aux tensions de vapeur faibles, les percussions correspondantes sont imputables à un nombre n_2 de molécules diffusant en sens inverse. $n_1 - n_2$, rapporté aux dimensions particulaires, correspond à la valeur du gradient de tension de vapeur.

Une fois le régime permanent de diffusion établi, en tous points de l'espace entourant la gouttelette règne en effet une seule et même pression, la pression atmosphérique, correspondant à un nombre N bien défini de molécules par unité de volume. Ce nombre total N est en fait la somme constante de deux termes: dont les valeurs extrêmes sont n'_1 molécules d'air et n_1 molécules de vapeur au voisinage de la région source à tension de vapeur P_1; n'_2 molécules d'air et n_2 molécules de vapeur dans la zone des derniers libres parcours moléculaires de la région puits à tension de vapeur P_2.

L'effet cinétique des molécules d'air est, à l'échelle de la particule, responsable du mouvement brownien habituel, celui des molécules de vapeur diffusant de la zone source vers la zone puits se traduit par un

bombardement différentiel de la particule suivant une direction privilégiée, celle empruntée par le transfert de vapeur.

La force exercée sur la particule soumise à un gradient de pression partielle de vapeur se calcule aisément, de la même façon que dans le cas où la particule est soumise à un gradient global de pression d'origine thermique. Pour des particules de dimensions supérieures au libre parcours moyen, la force exercée est simplement proportionnelle au rayon; c'est le carré du rayon qui intervient lorsque la particule est plus petite que le libre parcours moyen.

L'intégration pour un temps T des forces de percussion ainsi développées sur la particule, en supposant par exemple les chocs élastiques, représente l'expression de la résistance donnée par la loi de STOKES pour le déplacement d'une sphère particulaire en milieu visqueux aux faibles nombres de REYNOLDS. On voit en particulier que pour des particules supérieures à 0,5 μ l'expression de la vitesse de déplacement n'est plus fonction du rayon r de la particule. Aux valeurs de r inférieures à celles du libre parcours moléculaire l'expression de la vitesse est plus complexe, elle est fonction de r_2 et la correction de CUNNINGHAM doit être introduite.

Les équations du mouvement de la particule sont assez complexes si on cherche à les établir en tenant compte de toutes les forces exercées sur elle.

En négligeant la pression osmotique du nuage particulaire lui-même considéré comme une atmosphère, et en faisant abstraction pour les mesures radiales de la composante verticale due à l'action de la pesanteur seule, on obtient pour la vitesse de déplacement d'une grosse particule en régime permanent de diffusion d'une vapeur une relation simple de proportionalité: $V = C\frac{dp}{dx}$ où $\frac{dp}{dx}$ est le gradient de pression de vapeur partielle et C un facteur dépendant de la température, de la pression globale, des constantes de la vapeur utilisée.

Des mesures systématiques portant sur différentes vapeurs aussi diverses que l'eau, le benzène, l'alcool ou le trichlorétylène ont montré que le déplacement des particules était bien dû à un effet cinétique pur quelles que soient les propriétés électriques des molécules utilisées.

En utilisant des aérosols de magnésie ou de produits de combustion de tabac et en favorisant la coagulation pour obtenir des particules supérieures à 0,5 μ, donc facilement observables, on se place dans le cas où les dimensions particulaires n'interviennent pas dans l'expression de la vitesse. Il s'en suit que dans le cas de la condensation par exemple on observe un afflux régulier du nuage particulaire sur la gouttelette en voie de condensation; chaque particule étant animée, aux fluctuations près, d'une vitesse sensiblement égale à celle de ses voisines.

Lorsqu'il y a évaporation au contraire, la formule implique une répulsion non sélective. Pour des forces supérieures à celle de la pesanteur les frontières de l'espace noir sont alors nettes, ce qui avait déjà été signalé dans le cas de la répulsion thermique.

Ce mécanisme de capture par cinétique moléculaire est totalement différent de celui déjà étudié par ALBRECHT, BRUN, et d'autres chercheurs. Il se situe à une autre échelle physique et permet la capture de particules submicroscopiques pour lesquelles le coefficient de captation serait nul en mécanique classique.

Dans le cas d'une gouttelette par exemple, cette capture ne se réalise que lorsqu'il y a condensation, mais si dans une phase d'évaporation ultérieure aucun processus de capture n'est plus possible, il ne faut pas oublier que les particules déjà captées n'en demeurent pas moins incorporées à la phase liquide, et dissoutes par surcroît si elles étaient solubles.

Cette dernière remarque permet d'expliquer certaines observations faites en atmosphère libre ou en laboratoire.

WIGAND et plus récemment PLUVINAGE avaient déjà constaté la disparition précédée d'une décroissance rapide, du nombre des noyaux de condensation dans les nuages. Il ne faut pas oublier que les gouttelettes composant le nuage sont en perpétuelle évolution, passant en moyenne la moitié de leur vie en période de condensation, l'autre moitié en période d'évaporation. Dans la première phase le mécanisme de capture cinétique intervient pour ramasser dans un sillage, d'ailleurs supérieur au diamètre de la gouttelette, toutes les particules submicroscopiques en suspension dans l'atmosphère.

Il se produit ainsi un véritable filtrage de l'air. Dans un nuage déjà âgé, tous les noyaux de condensation, même les plus petits, même ceux qui étaient restés passifs, finissent par être captés après un temps plus ou moins long, d'ailleurs facile à calculer lorsque l'on connaît le nombre de gouttelettes par unité de volume et leur répartition dimensionnelle.

On voit facilement que dans un nuage qui comprendrait n gouttelettes de rayon α par centimètre cube, la capture totale par cinétique moléculaire des petites particules présentes dans l'espace intergouttelettes interviendrait au bout d'un temps T donné par l'expression:

$$T = \frac{1}{K \cdot K' \cdot \eta \cdot \pi \alpha^2 V}$$

exprimant le temps nécessaire pour que 1 cm³ de l'espace soit balayé par la somme des sillages $n \pi \alpha^2$ des gouttelettes tombant avec la vitesse V cm sec^{-1}, K étant un coefficient représentant pour le temps T considéré la fraction consacrée aux processus de condensation. K' traduisant le «coefficient de captation» toujours supérieur à 1 en processus cinétique et tenant compte par conséquent aussi bien des gradients de tension de vapeur autour de la gouttelette que de l'incidence des dimensions particulaires en fonction du libre parcours moyen.

Ainsi par exemple dans un nuage conventionnel qui comprendrait par cm³ 1000 gouttelettes de 5 μ de rayon, la purification complète de l'atmosphère serait obtenue en moins de 2 heures et demie en supposant que les processus de condensation ne s'opèrent que pendant la moitié de ce temps et en prenant 1 pour coefficient de captation cinétique, autrement

dit en négligeant systématiquement l'épaisseur de la couche limite et l'influence des gradients de tension de vapeur.

Un nuage comportant 100 gouttelettes de 10 μ de rayon demanderait environ 1 h 40 min avec les mêmes hypothèses.

Ces chiffres ne traduisent évidemment que des ordres de grandeur puisque le coefficient K dépend des conditions d'évolution du nuage considéré et ne peut être que très approximativement évalué. Ils donnent néanmoins des temps très vraisemblables en bon accord avec les valeurs déjà trouvées pour la décroissance du nombre des noyaux de condensation dans une atmosphère nuageuse.

Bien entendu le mécanisme de capture classique au cours de l'écoulement hydrodynamique viendra s'ajouter aux effets cinétiques purs et sera plus particulièrement responsable de la capture des grosses particules pour lesquelles les forces de gravité seront supérieures aux forces de capture par cinétique moléculaire.

Si par la suite le nuage disparaît, même sans avoir précipité, il ne laissera dans l'atmosphère qu'un noyau par gouttelette évaporée. Mais ce noyau aura une histoire, il ne sera pas seulement le noyau de condensation primitif, origine de la gouttelette, il aura été enrichi par l'apport de toutes les particules captées pendant les périodes de condensation.

On voit donc que les formations nuageuses en général, même si elles ne se résolvent pas en pluie, contribuent à purifier l'atmosphère en réduisant le nombre des particules submicroscopiques en suspension. A l'échelle de l'atmosphère terrestre dans son ensemble, ce mécanisme doit pour une part non négligeable contribuer à fixer l'équilibre moyen de la turbidité.

Les processus de capture sont encore plus importants lors des phénomènes de sublimation inverse sur les particules de phase glace dans les nuages d'eau surfondue. Les gradients de tension de vapeur sont alors considérables. C'est là une explication simple des clichés de cristaux de glace pris par MOTO KUMAI au microscope électronique.

On peut donc affirmer que toute particule submicroscopique existant dans l'atmosphère se retrouvera assez rapidement captée par les éléments du nuage, même si cette particule, non hygroscopique, ne peut servir de noyau de condensation aux sursaturations habituellement rencontrées dans l'atmosphère.

Des particules à propriétés glaçogènes pourront donc intervenir et provoquer la formation de la phase glace à un moment quelconque de la vie du nuage sans avoir été pour cela à l'origine d'une gouttelette dans les toutes premières phases de la condensation. Une étude portant sur les particules glacées contenues dans un brouillard d'eau surfondue à un moment donné de son évolution n'est donc pas représentative du nombre et des propriétés des noyaux de congélation naturels présents dans l'atmosphère. Ce n'est qu'après un temps de l'ordre de l'heure, ou même de plusieurs heures, qu'un semblable bilan pourrait être dressé si toutefois la stabilité du nuage le permettait et sans que l'on puisse faire la part

des particules glaçogènes captées à nouveau par les très forts gradients entourant les cristaux de glace déjà formés.

On peut expliquer également ainsi que même à température négative constante, il existe une formation continue de particules glacées au sein d'un nuage; la fréquence d'apparition des cristaux de glace étant, elle, fonction de la richesse en noyaux glaçogènes de la masse d'air considérée.

Enfin pour certains types de nuages frontaux à évolution lente où les courants ascendants sont de l'ordre de quelques centimètres par seconde la masse nuageuse fait effet de filtre. Au voisinage immédiat de la frontière supérieure du nuage, comme conséquence du mouvement relatif de chute de l'ensemble des éléments du nuage aux vitesses de la loi de Stokes, il existera une zone pratiquement dépourvue de noyaux de condensation.

Dans cette zone située au-dessus et en dehors du nuage lui-même, la sursaturation, faute de noyaux de condensation efficients, pourra atteindre des valeurs relativement élevées, suffisantes en tout cas pour que les quelques noyaux d'efficacité réduite qui auraient échappé au filtrage puissent devenir actifs et condenser à eux seuls la vapeur d'eau en excès. Les gouttelettes ainsi formées croîtront d'autant plus rapidement qu'elles seront moins nombreuses. Il se formera à la partie supérieure du nuage des éléments susceptibles de déclencher une précipitation par les processus de coalescence au cours de leur chute.

Il ne nous a jamais été possible jusqu'à présent d'observer en laboratoire un quelconque processus de condensation directe sur des particules de fumées d'iodure d'argent introduites dans un brouillard d'eau en surfusion. Ces particules ne remplissent certainement pas en général le rôle de noyau de condensation aux faibles sursaturations rencontrées dans la nature.

Comme l'apparition de la phase glace suit immédiatement l'introduction d'un aérosol d'iodure d'argent il est indispensable d'admettre que c'est le contact direct d'une particule et d'une gouttelette qui est à l'origine de la formation d'un cristal de glace.

Aux faibles vitesses de Stokes, pour les particules les plus fines produites par brûleurs à flamme, le coefficient de captation des gouttelettes devient pratiquement nul si l'on considère le mécanisme d'Albrecht. Le mécanisme de capture cinétique rend compte au contraire dans ce cas de l'efficacité d'une dispersion fine des particules d'iodure d'argent.

La conclusion pratique que l'on peut formuler est que l'insémination artificielle de nuages par des aérosols à propriétés particulières sera d'autant plus efficace — la question de dimension critique du germe mise à part — que la particule sera plus petite, que l'effet cinétique de capture sera plus grand devant les forces de gravité.

La pulvérisation d'eau, en tant que moyen de dépoussiérage d'une atmosphère, permet la capture des plus grosses particules par la mécanique d'Albrecht, l'addition de produits mouillants aujourd'hui de

pratique courante dans les locaux industriels et les mines a sans doute pour effet une meilleure pénétration dans la goutte des poussières difficilement mouillables, mais la rencontre préalable de la poussière par la goutte selon un coefficient de captation déterminé est une condition impérative.

On peut se demander si les forces de VAN DER WAALS ne seraient pas suffisantes pour conserver le contact goutte — poussière graisseuse au cours de la chute, et si l'efficacité du procédé ne viendrait pas d'un abaissement de la tension de vapeur de la goutte captatrice; abaissement entraînant pour des conditions favorables d'ambiance une capture efficace des petites particules par le mécanisme de cinétique moléculaire.

Des pulvérisations de solutions de chlorure de calcium par exemple permettraient un dépoussiérage plus efficace des très petites particules en combinant les deux mécanismes de capture.

Enfin, on peut ainsi expliquer que, dans une certaine mesure, tout corps en voie d'évapo-transpiration se trouve, au moins pour certaines vitesses de ventilation, protégé contre la pollution par les particules submicroscopiques. En matière de bioclimatologie il peut y avoir là un facteur physique non négligeable de défense soit contre des micro-organismes, soit contre certaines particules toxiques.

L'utilisation généralisée des particules submicroscopiques témoins pour matérialiser la diffusion moléculaire d'un gaz ou d'une vapeur permet également l'étude visuelle directe des processus d'échange dans les problèmes où la notion de couche limite devient indispensable pour traduire les phénomènes observés. Il est en particulier possible d'examiner ainsi la déformation de la couche limite d'échange dans le cas d'une gouttelette faiblement ventilée.

551.524,7 : 551.571,7

Die Zustandswerte in der freien Atmosphäre bei Schauerniederschlägen.

Von

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Mit 4 Textabbildungen.

Zusammenfassung. Radiosondenergebnisse von 1664 Aufstiegen der Monate Mai bis September 1949 bis 1953 in München-Riem werden hinsichtlich der Bildung von Gewittern und Schauern untersucht. Die Kondensationsfeuchtadiabate liegt an Gewittertagen höher als an Tagen ohne Gewitter; auch die 0^0C-Grenze erscheint angehoben. Die Zahl der Tage ohne Niederschlag und die Zahl der Gewittertage steigt mit wachsender Mitteltemperatur in der freien Atmosphäre. Während die Zahl der Tage mit Hagelfällen in Bayern von der Temperatur kaum abhängig erscheint, nimmt das vom Hagel betroffene Gebiet mit zunehmender Temperatur bedeutend zu. Niederschläge und Gewittertätigkeit werden von der Verteilung des vertikalen Temperaturgradienten mit der Feuchtigkeit stark abhängig gefunden. Aus dieser Abhängigkeit wird eine als Labilitätsmaß geeignete Regel abgeleitet.

Summary. Results obtained by 1664 ascents of radiosondes during the months may till september 1949 to 1953 at Munich-Riem are evaluated with regard to the formation of thunderstorms and showers. On days with thunderstorms the moist-adiabatic lies at a higher level than on days without; the 0^0C-level appears to be lifted as well. The number of days without precipitation and the number of thunderstorm days increase with growing mean temperature in the free atmosphere. Whereas, in Bavaria, there is hardly any relation between the number of days with hail and temperature, the region covered by hail grows considerably in extent with increasing temperature. Precipitation and thunderstorm activity are found to be strongly dependent on the distribution of the vertical temperature gradient and humidity. From this dependence a rule is derived which may be used as a measure for instability.

Résumé. Etude de 1664 radiosondages des mois de mai à septembre 1949 à 1953 à München-Riem du point de vue de la formation des orages et des averses. L'adiabatique humide est plus élevée lors des jours d'orage qu'en l'absence de ceux-ci; l'isotherme de zéro degré semble aussi plus élevée. Le nombre de jours sans précipitations et celui des jours d'orage croissent avec la température moyenne dans l'atmosphère libre. Tandis qu'en Bavière le nombre de jours de grêle semble indépendant de la température, la surface des régions grêlées augmente nettement avec elle. Les précipitations et l'activité orageuse dépendent fortement de la distribution du gradient vertical de température selon l'humidité; de cette dépendance on peut tirer une règle servant de critère de labilité.

Unsere Kenntnis von den atmosphärischen Zuständen, die zu Schauerniederschlägen führen, bedarf noch wesentlicher Ergänzung. Die älteren Arbeiten auf diesem Gebiet ziehen großenteils nur die Temperaturschichtung oberhalb des Kondensationsniveaus der kräftig durchmischten bodennahen Schicht zur Erklärung der Schauerbildung heran. Demgegenüber weisen neuere Arbeiten besonders auf die Rolle der Feuchtigkeit in den höheren Schichten hin.

H. FAUST [*1*] schuf auf der Basis einer statistischen Untersuchung der Feuchteschichtung an Gewittertagen den Begriff der „Verdunstungslabilität", gedacht als Labilitätsmaß für den Gebrauch des Synoptikers; auf der gleichen Linie liegt der Labilitätsbegriff von A. SIMILÄ [*2*]. Dasselbe Problem wird auch von H. F. SCHMIDT [*3*], H. STOMMEL [*4*] und J. M. AUSTIN [*5*] aufgegriffen. Diese Autoren behandeln insbesondere die Tatsache der Durchmischung der im Cumulus aufsteigenden Luft mit der Umgebungsluft, um eine Reihe vorher nicht erklärter Diskrepanzen zu beseitigen. FAUST und AUSTIN stützen sich auf Statistiken, um ihre Anschauungen zu unterbauen.

In Ergänzung der genannten Arbeiten ist es vielleicht von Interesse, einmal auf Grund des Materials einer einzelnen, längere Jahre mit dem gleichen Verfahren arbeitenden aerologischen Station eine Zusammenstellung von Meßergebnissen bei sommerlichen Konvektionsschauern zu geben, das als Unterlage für weitere Betrachtungen auf diesem Gebiet dienen kann, zumal das bisher zur Verfügung stehende Material noch nicht gerade reichhaltig genannt werden kann.

An der Aerologischen Station München-Riem werden seit 1947 Radiosonde- und Radiowindmessungen mit amerikanischem Gerät durchgeführt. Den hier gezeigten Ergebnissen liegen Werte von insgesamt 1664 Aufstiegen zugrunde, die in den Monaten Mai bis September der Jahre 1949 bis 1953 durchgeführt wurden.

Die Bildung sommerlicher Schauer hängt erfahrungsgemäß von folgenden Größen ab:

1. Vom vertikalen Temperaturgradienten der ungestörten Luft.
2. Vom Wasserdampfmischungsverhältnis innerhalb der bodennahen Schicht.
3. Vom allgemeinen Temperaturniveau.

Diese Zustandsdaten sollen auch hier als kennzeichnend für die Bereitschaft zu Schauerniederschlägen betrachtet werden.

Die Ausgangssituation bei Cumulusbildung wird auf einem thermodynamischen Diagramm durch den Punkt bestimmt, in dem die den atmosphärischen Zustand charakterisierende Temperaturkurve diejenige Kurve maximalen Mischungsverhältnisses schneidet, die den Feuchtigkeitsgehalt der kräftig durchmischten bodennahen Schicht kennzeichnet. An diesem Punkt beginnt die Kondensation. Ein ohne Durchmischung isoliert aufsteigendes Luftteilchen würde von hier ab unter ständiger Kondensation von Wasser der durch diesen Punkt verlaufenden Feuchtadiabate folgen, vorausgesetzt, daß die Temperaturschichtung hinreichend labil ist. Im deutschen thermodynamischen Diagrammpapier sind die

Feuchtadiabaten numeriert gemäß der potentiellen Temperatur (in °C) auf der Trockenadiabaten, der sich die Feuchtadiabate bei fortschreitendem Ausfall des gesamten Wassergehalts der Luft asymptotisch nähert. Diese Nummer liegt also um so höher, je höher die Temperatur im Kondensationspunkt und je höher der Wasserdampfgehalt in der durchmischten bodennahen Schicht ist. Eine statistische Betrachtung der Häufigkeitsverteilung der Feuchtadiabaten durch den Kondensationspunkt kann also zeigen, wie das Zusammenspiel zwischen der Feuchte in der bodennahen Schicht und dem allgemeinen Temperaturniveau bei verschiedenen Wetterverhältnissen wirklich aussieht.

Eine solche Darstellung gibt Abb. 1. Da es sich um alle in München-Riem während der genannten Monate durchgeführten Aufstiege handelt, sind hier auch nicht realisierte Zustände erfaßt, z. B. solche, bei denen es überhaupt nicht zu Konvektionsbewölkung kam, da die Bodenschicht nicht hinreichend erwärmt wurde oder starke Turbulenz in der Höhe die sich bildende Bewölkung zerstörte. Aus der genannten Zahl von 1664 Aufstiegen wurden 1083 Fälle zusammengefaßt, bei denen innerhalb 6 Stunden nach dem Aufstiegstermin weder Niederschlag noch Gewitter beobachtet wurde. Diese Tage ohne Niederschlag sind in den Sommermonaten durch eine niedrige Nummer der Kondensationsadiabaten charakterisiert. Diesen Fällen gegenüber stehen die Tage mit Niederschlag innerhalb 6 Stunden nach der aerologischen Messung. Hier sind 581 Fälle erfaßt. In 214 Fällen aus der Gesamtzahl wurden innerhalb 6 Stunden nach der Messung Gewitter beobachtet, wobei alle typisch gewittrigen Erscheinungen (Ferngewitter, „Donner gehört“ und Wetterleuchten) mitgezählt wurden. Die Nummern der Feuchtadiabaten, der Fälle mit Niederschlag liegen im Mittel um 3°C höher, die mit Ge-

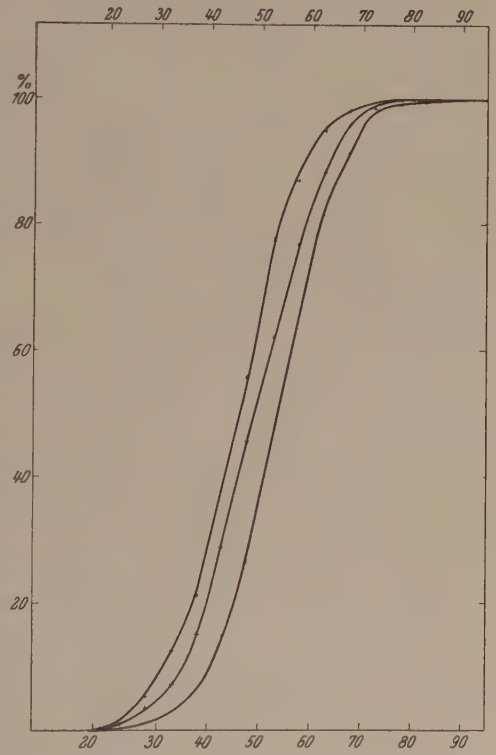

Abb. 1. Häufigkeitssummen der Kondensationsadiabaten nach den Aufstiegen von München-Riem 1950/53 (Monate Mai—September). Abszisse: Nummer der Kondensationsadiabaten. Ordinate: Häufigkeitssumme in Prozenten. Links: 1083 Termine ohne Niederschlag innerhalb 6 Stunden nach dem Aufstieg. Mitte: 581 Termine mit Niederschlag innerhalb 6 Stunden. Rechts: 214 Termine mit Gewitter innerhalb 6 Stunden.

witter um 8°C höher als bei den Fällen ohne Niederschlag. Dabei nähert sich die Kurve der Niederschlagsfälle für die niedrigen Nummern der Feuchtadiabaten der der Fälle ohne Niederschlag, für die höheren Nummern der Kurve der Gewitterfälle. Der Grund hierfür liegt darin, daß mangels der Genauigkeit der Beobachtung Niederschläge mit und ohne Schauercharakter nicht unterschieden werden konnten. Der untere Teil der Kurve enthält also wohl mehr Niederschläge ohne Schauercharakter, der obere mehr Gewitterschauer. Tabelle 1 zeigt diese Ergebnisse noch einmal zahlenmäßig.

Tabelle 1. *Häufigkeit der Nummern der Kondensationsfeuchtadiabaten in München-Riem.*

	Termine ohne Niederschlag innerhalb 6 Stunden	Termine mit Niederschlag innerhalb 6 Stunden	Termine mit Gewitter innerhalb 6 Stunden
25% der Fälle unterhalb	39	41	47
50% der Fälle zwischen .	40 bis 52	42 bis 56	48 bis 60
25% der Fälle oberhalb .	52	57	61

Für die weiteren Untersuchungen wurden nur noch die 15-Uhr-(GCT-) Aufstiege zugrunde gelegt, da ja die Hauptschauertätigkeit in den Nachmittags- und Abendstunden liegt.

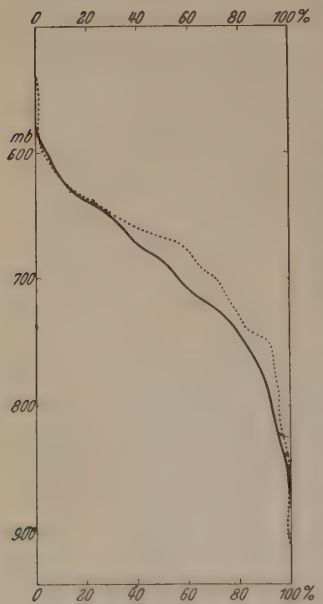

Abb. 2. Häufigkeitssummen der Höhenlage der Nullgrad-Grenze in München-Riem (Monate Mai bis August 1950/53) in Prozenten oberhalb eines bestimmten Druckniveaus. Ausgezogene Kurve: Fälle ohne Gewitter. Gestrichelte Kurve: Fälle mit Gewitter.

Eine erste Übersicht über die Temperaturverhältnisse gibt die Höhenlage der Nullgrad-Grenze (Abb. 2). Man sieht, daß im Mittel der Gewitterlagen die Nullgrad-Grenze etwa 20 mb höher liegt als in den Fällen ohne Gewitter, in mittleren Höhen der Troposphäre ist es also bei Gewitterlagen im allgemeinen wärmer als im Durchschnitt. Eine Ausnahme machen die Situationen mit extrem hoch liegender Nullgrad-Grenze. Hier werden wahrscheinlich die Hochdruckwetterlagen mit starkem Absinken und schwachem Temperaturgradienten erfaßt. Bei diesen Lagen geht die Feuchtigkeit in der freien Atmosphäre stark zurück und die Gewitterbildung wird behindert.

Nach dem Gesagten erscheint es wichtig, den Zusammenhang zwischen der Temperatur und der Feuchte auch gerade in den Höhen zu kennen, wo Cumulonimbusmassen sich am stärksten entwickeln.

Als charakteristisch für die Temperatur wurden dabei die Niveaus 850 und 500 mb angesehen, das arithmetische Mittel der Tempera-

tur dieser beiden Schichten gibt die Grundlage für die Darstellung der Abb. 3. Für den energieliefernden Vorgang der Kondensation ist die spezifische Feuchte oder das Mischungsverhältnis charakteristisch. Das Mischungsverhältnis und damit die Größe der freiwerdenden Kondensationswärme

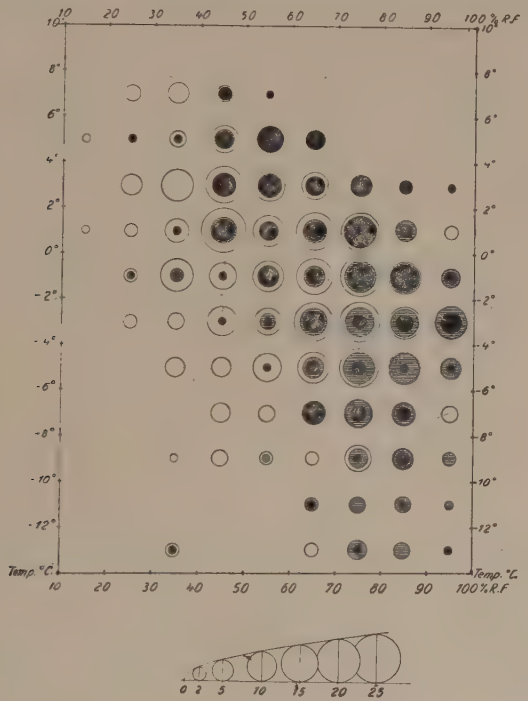

Abb. 3. Beziehung der Fälle ohne Niederschlag, mit Niederschlag und mit Gewitter zur mittleren Lufttemperaturen in der Höhe (½[T 850 + T 500]) und zur mittleren relativen Feuchte (½ [RF 850 + RF 700]). Offene Kreise bzw. Kreisringe: Fälle ohne Niederschlag.
Schraffierte Kreise bzw. Kreisringe: Niederschlag innerhalb 6 Stunden.
Schwarze Kreise bzw. Kreisring: Gewitter innerhalb 6 Stunden.
Der Flächenmaßstab ist unter der Abbildung gegeben.

geht aber mit abnehmender Temperatur stark zurück, so daß im 500-mb-Niveau nur noch in seltenen Fällen eine wesentliche Wärmemenge freigesetzt wird. Es wurde daher für die Feuchteverteilung das arithmetische Mittel der relativen Feuchte in den Niveaus 850 und 700 mb als maßgebend angesehen. Daß die bequemer zugängliche relative Feuchte anstelle des Mischungsverhältnisses benutzt werden darf, wurde durch Kontrollrechnungen geprüft. Es ergab sich, daß die so entstandenen Fehler gegenüber den möglichen Meßfehlern keine wesentliche Rolle spielen.

Die Abbildung zeigt, daß bei niedrigen relativen Feuchten Niederschläge nur selten vorkommen, einige Gewitter treten noch bei hoher Mitteltemperatur auf. Bei hoher Mitteltemperatur überwiegt allgemein die Zahl der Gewitter erheblich die der gewitterlosen Niederschläge, bei

tiefen Mitteltemperaturen ist es umgekehrt. Trotz dieser allgemeinen Tendenz ist es nicht leicht möglich, etwa ein quantitatives Maß dieser Einflüsse festzulegen, da in einem großen Gebiet der Darstellung Fälle ohne Niederschlag und solche mit Niederschlag und mit Gewitter der Größenordnung nach gleich häufig vorkommen. Die Tabelle 2 zeigt eine zahlenmäßige Auswertung dieser Darstellung.

Tabelle 2. *Mitteltemperatur der Druckflächen 850 und 500 mb in ihrer Beziehung zu Hagelfällen, Gewitter und Niederschlag.*
(15-Uhr-Aufstiege München-Riem, Mai bis September 1949—1953.)

Mitteltemperatur ½ (T 850 + T 500)	unter −10° C	−9,9 bis −5,0°C	−4,9 bis −0,1°C	−0,0 bis +4,9°C	über +4,9° C
Fälle insgesamt	27=100%	113=100%	252=100%	189=100%	26=100%
Fälle ohne Niederschlag	6=22,2%	50=44,2%	129=51,2%	101=53,4%	16=61,5%
dabei höchste vorkommende Feuchte	82%	88%	89%	92%	(70%)
Fälle mit Gewitter in München	4=14,8%	23=20,3%	60=23,8%	76=40,2%	9=34,6%
dabei niedrigste vorkommende Feuchte	59%	59%	26%	25%	(26%)
Fälle mit Hagel in Bayern	13=48,2%	52=46,0%	103=40,8%	91=44,2%	14=53,8%
Zahl der hagelbetroffenen Gemeinden	190	702	2,203	4,029	450
Zahl der Gemeinden pro Fall	7,0	6,2	8,7	21,3	17,3
Zahl der Gemeinden pro Hageltag	14,6	13,5	21,4	44,3	32,1

Die Tabelle zeigt, daß die Gewitterwahrscheinlichkeit mit zunehmender Mitteltemperatur erheblich wächst; dabei können bei höheren Mitteltemperaturen noch bei recht geringer Feuchte in der Höhe Gewitter auftreten. Unter „Gewitter in München" wurde auch hier jede Beobachtung von Gewittertätigkeit verstanden. Mit Rücksicht auf die große wirtschaftliche Bedeutung der durch Hagel verursachten Schäden wurde die Tabelle noch durch die Angabe von Hagelbeobachtungen ergänzt. Es muß hierzu bemerkt werden: Für einen statistischen Vergleich ist die Dichte der Hagel meldenden Wetterbeobachtungsstationen zu gering. Die Zahlen wurden daher dem Material der Bayerischen Staatlichen Hagelversicherung entnommen. Dieses Material erstreckt sich einerseits auf ganz Bayern, also auch auf Gebiete, für die ein aerologischer Aufstieg in München keine repräsentative Zustandskurve mehr ergibt, andererseits sind die Beobachter der Hagelversicherung nicht gleichmäßig verteilt. Versicherungsabschlüsse weisen vorzugsweise solche Gebiete auf, die besonders wertvolle hagelempfindliche landwirtschaftliche Kulturen anbauen und für die daher ein besonders großes Risiko besteht. Diese Einschränkung erscheint jedoch für den Vergleich nicht

allzu schwerwiegend. Im Gegensatz zur Gewitterhäufigkeit zeigt die Häufigkeit der Hagelfälle kaum einen Gang mit der Mitteltemperatur. Sehr ausgeprägt ist jedoch die Beziehung zwischen der Mitteltemperatur und der Zahl der von Hagelschäden betroffenen Gemeinden, diese wächst bei höherer Temperatur stark an.

Wesentlich charakteristischer als die Beziehung zwischen Mitteltemperatur und Feuchtigkeit zeigt sich im Zusammenhang mit der Schauerbildung die Kopplung zwischen dem vertikalen Temperaturgradienten und der Feuchtigkeit in der Höhe. In der Darstellung der Abb. 4 wurde für jeden 15-Uhr-Aufstieg der Jahre 1950 bis 1953 die Differenz der Temperaturen der Hauptdruckflächen 850 und 500 mb dem arithmetischen Mittel der relativen Feuchte der Flächen 850 und 700 mb gegenübergestellt. Da sich die Darstellung auf alle 15-Uhr-Aufstiege bezieht, sind in ihr auch alle Fälle enthalten, in denen es tatsächlich deshalb nicht zur Schauerbildung kam, weil großräumige Vorgänge, wie Strömungsdivergenz oder allgemeines Absinken, die Auswirkung an sich vorhandener Labilität verhinderten. Ebenso wurden Luftmassenwechsel oder

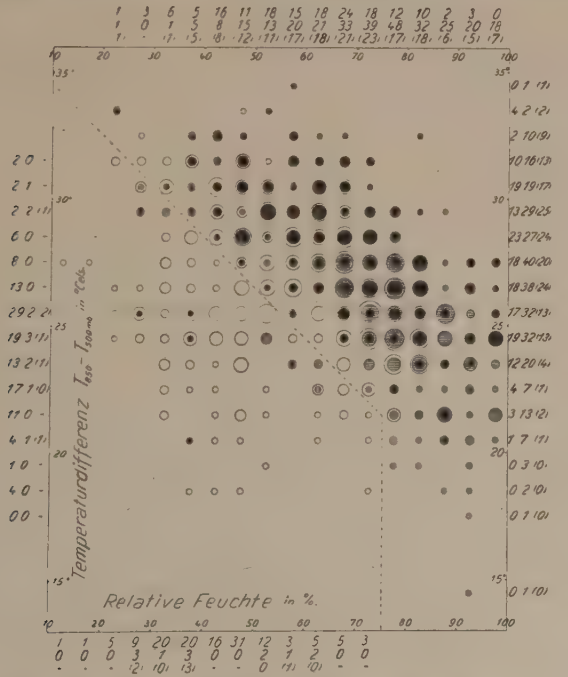

Abb. 4. Beziehung der Fälle ohne Niederschlag und mit Gewitter zum mittleren vertikalen Temperaturgradienten (T 850—T 500) und zur mittleren relativen Feuchte (½ [RF 850 + 700]).
Bedeutung der Kreisflächen wie in Abb. 3.
Die Zahlen am Rande geben an:
Oberste Reihe (erste Spalte): Fälle ohne Niederschlag.
Zweite Reihe (Spalte): Fälle mit Niederschlag.
Dritte Reihe (Spalte): davon Fälle mit Gewitter.
Die Zahlen beziehen sich jeweils auf das durch die gestrichelten Geraden abgeteilte Gebiet.

Frontdurchgänge innerhalb sechs Stunden nach dem Aufstieg nicht besonders ausgeschlossen. Diese selteneren Fälle gehen aber offenbar weitgehend in der großen Zahl unter. Schließlich wurde mit Rücksicht auf Beobachtungsunsicherheiten kein Unterschied zwischen Schauer- und sonstigem Niederschlag gemacht, daher sind bei großen relativen Feuchten auch Niederschlagsfälle ohne Schauercharakter miterfaßt.

Wie in der Darstellung der Beziehung zwischen Feuchte und Mitteltemperatur überlappen sich auch in Abb. 4 die Gebiete mit und ohne Niederschlag, doch erscheint bemerkenswert, daß in einem weiten Bereich Gewitter und Niederschlag fast völlig fehlen. Die Grenze des Gebietes mit äußerst seltenem Niederschlag verläuft geradlinig aus dem Gebiete niedriger Feuchte bei großem Temperaturgradienten durch den Punkt 35% bei 30° C Temperaturdifferenz auf der Zustandskurve zwischen 850 und 500 mb bis zu dem Punkt 75% relativer Feuchte bei 22° C Temperaturdifferenz. Von diesem Punkte an ist bei geringen Temperaturgradienten nur noch die Feuchte für die Neigung zu Niederschlag kennzeichnend. Relative Feuchte über 75% war bei dem vorliegenden Beobachtungsmaterial stets von Niederschlag begleitet, geringere relative Feuchte nie. Innerhalb des trockenen Bereichs stehen 12 Fällen von Niederschlag 131 niederschlagsfreie Fälle gegenüber. Die Gerade, die in der Darstellung beide Gebiete voneinander trennt, läßt sich als Zahlenregel wiedergeben: Schauer treten praktisch nicht auf, solange die relative Feuchte zwischen 850 und 700 mb unterhalb eines Wertes von 75% bei (T 850—T 500) unter 22° C oder

$$\text{r. F.} = 185 - 5\,(T_{850} - T_{500})$$

liegt, falls der Wert der Temperaturdifferenz in der Klammer 22°C überschreitet. Umgekehrt ist die Schauerwahrscheinlichkeit groß, sowie die Feuchte oberhalb 75% oder oberhalb des durch die obige Formel gegebenen Wertes liegt. Diese Regel kann möglicherweise praktische Dienste statt eines Labilitätsmaßes leisten. Ihre Anwendung ist ohne Zeichnung und Auswertung einer Zustandskurve möglich und ist frei von der Unsicherheit, die insbesondere dann in der richtigen Bestimmung des Cumuluskondensationsniveaus liegt, wenn die Feuchteschichtung am Boden sehr großem Wechsel unterworfen ist. Zur Anwendung obiger Regel braucht man lediglich die durch Funk oder Fernschreiber übermittelten Werte der Temperatur der Flächen 850 und 500 mb und die relativen Feuchten der Flächen 850 und 700 mb.

Am Rande der Abb. 4 sind für die Einteilung beider Koordinaten die Häufigkeiten der Beobachtung niederschlagsfreien Witterungsverlaufs, der Fälle mit Niederschlag und der Fälle mit Gewitter zahlenmäßig noch einmal aufgetragen. Die Zahl der ersten Spalte (obersten Reihe) gibt die Fälle ohne Niederschlag, die der zweiten Spalte (Reihe) die mit Niederschlag, die eingeklammerte Zahl der dritten Spalte (Reihe) die Gewitterfälle an. Man sieht, daß bei großen Vertikalgradienten und niedrigen relativen Feuchten in der Höhe Niederschläge fast stets mit Gewittern verbunden sind, mit zunehmender Stabilität der Schich-

tung, aber auch mit zunehmender relativer Feuchte nimmt die relative Häufigkeit der Niederschläge ohne Gewitter zu.

Die Erklärung des aus Abb. 4 ersichtlichen Sachverhalts ist zweifellos auf dem von SCHMIDT, STOMMEL, AUSTIN und FAUST (l. c.) eingeschlagenen Wege zu suchen. Die Durchmischung mit trockener Luft aus der Umgebung der Wolke behindert die Cumulus-Entwicklung in der Höhe und damit die Schauerbildung sehr wesentlich. Sicher ist dieser Mischungsvorgang kein einseitiges Einsaugen von Außenluft ins Innere des aufsteigenden Cumulus. Die Wolke als optische Erscheinung ist durch den sichtbar von Kondensationsprodukten erfüllten Raum definiert. In der Höhe wird dieser Wolkenraum von einer Masse (Luft mit Kondensat) erfüllt, die mehrfach größer ist als die Masse der Luft aus Bodennähe, die die Wolkenbasis durchsetzt hat. Wie AUSTIN und FLEISHER [*6*] gezeigt haben, muß das so sein, man könnte sonst weder die Gestalt noch die Bewegung der Cumuluswolke erklären. Die Massenzunahme muß aus der Umgebungsluft stammen. Andererseits wird natürlich bei erheblicher Turbulenz in der Höhe auch sehr viel Wasser in Dampfform an die wolkenfreie Umgebungsluft abgegeben. Mit abnehmender Temperatur wird jedoch wegen des immer geringer werdenden Sättigungsdruckes in der Höhe immer weniger Kondensat verdampfen können. Bei der Betrachtung der Wolken und speziell durch Konvektion entstandener Wolken tut man sicher gut, nicht nur das sichtbare Gebilde als Träger der Zustandsänderungen anzusehen, sondern von dem Gesamtvorgang auszugehen, zu dem das Wiederverdampfen des Kondensats und die Übertragung des Dampfes an die Umgebung der Wolke genau so gehört wie die meistens in erster Linie behandelte Kondensation. Es erscheint eine lohnende Aufgabe, dieses Verhältnis auch einmal von der messenden Seite her anzugehen.

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Cloud Physics at the Meteorological Research Flight.

By

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With 10 figures.

Abstract. A review is given of the aircraft instrumentation used for cloud physics investigations. Below the cumuliform cloud the nature of the convection is examined by means of rapidly acting thermometers, hygrometers, hot wire anemometers and aircraft accelerometers. In the lowest 1000 feet where the lapse-rate is slightly super-adiabatic, continuously turbulent conditions are found. Above this bubbles or pulses 300—600 feet across rise sporadically in an environment whose lapse-rate is approximately dryadiabatic. Just below the cloud base the lapse-rate is usually stable and long wave fluctuations of temperature in the horizontal are found.

Within the cloud temperatures are difficult to measure accurately. Attempts to use vortex thermometers for this purpose have been unsuccessful. Vertical currents can be estimated roughly from aircraft displacements. Water content in cumuliform cloud probably attains local values of about 5 g/m^3 for short periods, but up to the present none of the instruments developed have been capable of measuring amounts of this magnitude. The progress made so far in developing hot wire water content meters and refrigerated icing disc meters is described.

Cloud particles can readily be sampled from aircraft when they are small but satisfactory methods have not yet been developed for the larger particles (e.g. hail, snow and rain). Droplet sampling over England has shown the presence of large droplets (100 microns diameter or more) in moderate sized cumulus clouds. Examples are shown of rain being produced by stratiform warm sector clouds with tops well below the freezing level and precipitation in large cumulus clouds apparently preceeding the ice crystal stage. A comparison between average cloud top temperatures for clouds which produce rain and for those whose tops are composed of ice crystals rather than supercooled droplets suggests that rainfall in England may often be produced in clouds in which the BERGERON mechanism does not operate.

Zusammenfassung. Es wird eine Übersicht über die für wolkenphysikalische Beobachtungen im Flugzeug verwendeten Instrumente gegeben. Mit Hilfe von Thermometern kurzer Einstelldauer, Hygrometern, Hitzdraht-Anemometern und Flugzeug-Beschleunigungsmessern wird die Konvektion unter Cumuluswolken studiert. In den untersten 300 m, wo der Temperaturgradient etwas überadiabatisch ist, werden ständig turbulente Verhältnisse gefunden. Oberhalb dieser Zone steigen in einer Umgebung mit ungefähr trockenadiabatischen Temperaturgradienten sporadisch Luftpakete oder

Blasen von etwa 100 bis 200 m Durchmesser auf. Knapp unterhalb der Wolkenbasis ist der Temperaturgradient meist stabil und es werden dort lange wellenartige Schwankungen der Temperatur in horizontaler Richtung gefunden.

Innerhalb der Wolke ist die genaue Temperaturmessung schwierig. Die versuchsweise Anwendung von „Vortex-Thermometern" blieb ohne Erfolg. Vertikale Luftbewegungen können aus der vertikalen Versetzung des Flugzeuges ungefähr abgeschätzt werden. Der Wassergehalt von cumulusartigen Wolken erreicht vermutlich stellenweise und für kurze Zeit Werte von 5 g/m³. Es ist jedoch mit keinem der bisher entwickelten Instrumente gelungen, einen derart hohen Wassergehalt zu messen. Die bisher erzielten Fortschritte bei der Entwicklung der Geräte zur Wassergehaltsmessung (Hitzdraht und gekühlte Eisansatz-Scheibe) werden mitgeteilt.

Wolkenteilchen können in einfacher Weise vom Flugzeug aus aufgefangen werden, wenn sie klein sind; doch sind für größere Teilchen (Hagel, Schnee, Regen) bisher keine zufriedenstellenden Methoden angegeben worden. Messungen der Tröpfchendurchmesser über England haben ergeben, daß in mäßig entwickelten Cumuluswolken große Tröpfchen (Durchmesser 100 μ oder mehr) vorhanden sind. Beispiele für die Erzeugung von Regen durch Stratus- (Warmsektor-)Wolken mit Gipfelhöhen unterhalb der 0°-Grenze und Niederschläge in großen Cumuluswolken, offensichtlich vor Erreichen des Eisstadiums, werden beschrieben. Ein Vergleich zwischen den Temperaturen in Gipfelhöhe für Wolken, aus denen Regen ausfällt, und für solche, deren oberste Teile eher aus Eiskristallen als aus unterkühlten Tröpfchen bestehen, scheint darauf hinzuweisen, daß in England der Regenfall häufig in Wolken entsteht, in denen der von BERGERON beschriebene Mechanismus nicht wirksam ist.

Résumé. L'auteur passe en revue les instruments utilisés sur les avions pour l'étude de la physique des nuages. On étudie la convection au-dessous des cumulus à l'aide de thermomètres à petite inertie, d'hygromètres, d'anémomètres à fil chaud et d'accéléromètres. Dans les 300 m. inférieurs ou le gradient de température est légèrement sur-adiabatique on trouve toujours une forte turbulence; au-dessous de cette zone, des paquets» d'air isolés, de 100 à 200 m. de diamètre, pénètrent dans un milieu à gradient quasi adiabatique. Immédiatement au-dessous de la base nuageuse, le gradient est en général stable et l'on y trouve des variations de température de type ondulatoire dans le sens horizontal.

A l'intérieur du nuage, la mesure de la température est difficile. L'emploi de thermomètres «Vortex» n'a pas eu de succès. Les déplacements verticaux de l'avion permettent d'estimer les mouvements de l'air selon la verticale. La teneur en eau de nuages cumuliformes atteint probablement et pour peu de temps des valeurs de l'ordre de 5 g/m³; toutefois aucun des instruments jusqu'ici proposés n'a pu mesurer des teneurs en eau aussi élevées. L'auteur expose les progrès réalisés dans le perfectionnement des instruments de mesure de la teneur en eau (fil chaud et disque à dépôt glacé).

Il est possible de capter facilement en avion les particules nuageuses tant qu'elles sont petites; lorsqu'elles sont plus grandes (grêle, pluie, neige), les méthodes font encore défaut. Des mesures de diamètre de gouttes en Angleterre ont montré qu'il y a des grosses gouttes (diamètre de 100 μ ou davantage) au sein de cumulus moyennement développés. L'auteur donne des exemples de formation de pluie à partir de stratus (secteur chaud) ayant leur sommet au-dessous de l'isotherme de zéro degré ainsi que de précipitations provenant de gros cumulus sans que le stade glacé ait été apparement atteint. Une comparaison entre les températures au sommet de nuages pluvieux et de nuages dont la partie supérieure est formée de cristaux plutôt que de gouttes en surfusion semble démontrer qu'en Angleterre la pluie prend souvent naissance au sein de nuages où le mécanisme décrit par BERGERON n'intervient pas.

I. Introduction.

The Meteorological Research Flight of the British Meteorological Office is located at Farnborough, Hampshire. At present it has four aircraft allocated solely for the purpose of meteorological research and is engaged on a wide variety of problems ranging from measurements of humidity, ozone, jet streams and clear air turbulence in the upper troposphere and lower stratosphere to investigations of fronts and cloud physics in the lower troposphere. My following remarks will be concerned only with the latter and I hope to say something about instrumentation and techniques used in this work as well as presenting some results. Owing to the large field covered many aspects will be reviewed very briefly. Our preoccupation with instrumentation is justified by the fact that the treatment of cloud physics in common with that of other meteorological problems is rapidly becoming more quantitative and reliable instrumental measurements are therefore very necessary. It must also be admitted that none of the main parameters required in calculations of cloud growth and rainfall processes e. g. temperature, vertical currents, water contents and particle size can be measured at present by any means with the required accuracy. Although some progress is being made, it will be some time before generally accepted measurements will be achieved from aircraft as many of the instrumental problems they present are extremely complex. Until these have been solved and there is high confidence in the accuracy of the readings there is little to sbe gained by producing the systematic sets of measurement demanded in [*1*].

II. Aircraft Instrumentation.

The instruments at present in use are mounted on the fuselage of a Hastings aircraft as shown in Fig. 1.

1. The nose attachment contains heated platinum wires in two channels arranged to have equal airflow over them in level flight and connected in the arms of a Wheatstone bridge. A gust normal to the line of flight produces a difference in the airflow over the two wires and this in turn produces an out of balance voltage from the bridge.

2. The vertical arm, which is retracted for protection into the fairing under the fuselage on take off or in cloud, has thin platinum wires at its ends both heated and unheated for use as hot wire anemometer and rapid response resistance thermometer elements respectively.

3. Conventional aircraft resistance thermometers of the flat plate type are mounted under the fuselage.

4. Tangential and axial type vortex thermometers are also mounted below the nose.

5. In addition hot wire water content meters are located there.

6. Standard rotating disc icing meters and the refrigerated type as well as a Smith's type icing indicator are also provided.

7. An impactor for droplet sampling is pushed out of the side during thesampling.

8. Air intakes are provided for crystal sampling in the nose and for supplying the hygrometers.

For good results detailed consideration must be given to the mounting and exposure of these instruments. In practice the best that can be done,

Fig. 1. Exterior of M. R. F. Hastings Aircraft.

1. Hot wire anemometer (vertical gusts).
2. Rapid thermometer and hot wire anemometer.
3. Flat plate resistance thermometers.
4. Axial vortex thermometer; *4'*. Tangential vortex thermometer.
5. Hot cylinder water content meter; *5'*. Hot wire water content meter.
6. Rotating disc icing meter; *6'*. Smith's icing detector.
7. Shutter in fuselage for droplet sampler.
8. Hygrometer air inlet; *8'*. Air inlet for crystal sampling.

however, is usually to mount them as far ahead of the propellers and as far away from the fuselage as is possible mechanically. In some cases, e. g. for water content meters, vortex thermometers and droplet samplers consideration should be given to the direction of the streamlines around the aircraft and how the cloud droplets will be deviated, before the instrument position is selected.

Fig. 2 shows the interior of the aircraft which is arranged as far as possible to provide laboratory conditions of working. Each table has a variety of power supplies available, and wiring direct to the element positions. As well as ordinary dial readings means are provided of photographing other instrument dials and continuous recording by multichannel galvanometer recorders. So far none of the instruments are in their final form and the layout is arranged for easy modification and further development.

Fig. 2. Interior of M. R. F. Hastings Aircraft.
1. Automatic Observer.
2. Galvanometer recorder.
3. Power supplies.
4. Working tables.

III. The Wind and Temperature Field below Cumulus Clouds.

Below the cloud the nature of the upwards transfer of heat and moisture is being examined by a group of instruments with rapid response comprising ultra rapid thermometers [2], automatic hygrometers, hot wire anemometers, and aircraft accelerometers. The results of a series of flights with these indicates that the nature of the convection is in the form of isolated bubbles or pulses rather than any cellular system, the general distribution being as shown in Figure 3.

—Ve PULSES, 4°F,
300—400 FT. ACROSS
TENDENCY FOR THERE TO BE OCCASSIONAL STABLE LAYERS IN CLEAR AIR ALONG THE SIDE OF THE CLOUD
DEVELOPING CLOUD
OCCASSIONAL+Ve PULSES 0·4°F, 300 FT., AWAY FROM CLOUD
CLOUD BASE

SUB-CLOUD LAYER	COMPLEX ISO-THERMAL OR INVERSION	AS BELOW	600 FEET, SOME 100 FEET	0·3°F AND 1·2°F	4 FT./SEC.	0·1 g FEWER QUIET PERIODS	MARKED LONG WAVE VARIATIONS OF AMPLITUDE 2°F AND WAVE-LENGTH 5000 FT. (400 FT.)
INTER-MEDIATE LAYER	ADIABATIC	DECREAS-ING NUMBER, IN GROUPS	600 FT., OCCASSION-ALLY 2500 FT.	0·3°F AND 3·5°F	5-8 FT./SEC.	ISOLATED, MANY QUIET PERIODS	LITTLE VARATION OF SIZE WITH HEIGHT. SOME HORIZONTAL GUSTS. TEMPORARY INVERSIONS OF 1°F AND 100 FT. THICK
CIRCA 1000 FT. LOWEST LAYER	SUPER-ADIABATIC	VERY MANY	VERY VARIABLE, MEAN 500 FT.	1·2°F AND 5·7°F	5-8 FT./SEC. OCCASSION-ALLY 15 FT/SEC.	CONTINU-OUSLY, SHARP-EDGED, OCCASSION-ALLY 0·3 g	NARROW IRREGULAR BOUNDARY
	LAPSE RATE	BUBBLE FREQUENCY AND CHARACTER-ISTICS	DIAMETER	TEMPER-ATURE EXCESS AND DEW-POINT EXCESS.	VERTICAL SPEED.	GUSTINESS AND BUMPS.	REMARKS

Fig. 3. Convection field below cumulus over land.

a) In the lowest 1000 ft. or so over land where the mean lapse rate is mainly superadiabatic they present a chaotic picture of many different sizes with a mean of about 500 ft. diameter and bumpiness is continuous. Temperature and dewpoint excess are respectively about 2°F and 6°F and rate of rise about 10 ft./sec.

b) Above this they are more organised and rise sporadically in a dry adiabatic lapse rate with an excess temperature of about 0.3° F. There is very little change of size with height.

c) Finally at about 400 ft. from the cloud base it is usually found that the lapse rate becomes more stable and the rate of rise of these pulses becomes very small. At this stable layer the convection appears to change its scale and produce cells of about 10 times the diameter of the pulses rising beneath.

IV. The Measurement of Temperature, Vertical Currents, Water Content and Particle Size.

A. Temperature.

Temperature in the clear air can be measured to an accuracy of about 1.0°F once the aircraft thermometer is calibrated in flight to establish the error in its reading due to kinetic heating. It is very desirable for buoyancy calculations to measure accurately the temperature difference between a cloud and its surroundings. Difficulties arise in this due to a combination of the kinetic heating effects, evaporation on the thermometer surface, the necessity of correcting for the vertical motion of the aircraft to a datum level in terms of the unknown in-cloud lapse rate and the effects of the different lags of the air speed indicator, altimeter and thermometer on the corrections which have to be applied.

It was hoped that vortex thermometers [*3, 4*] might be used to overcome some of these difficulties as they provide compensation for the kinetic heating effect and also centrifuge droplets to the outside of the vortex away from the sensing element. The results of a series of flight tests with these instruments are as follows:

1. In clear air both the tangential and axial types work efficiently up to at least a height of 20,000 ft. and indicated airspeed of 200 knots. The axial type has also been tested up to about 40,000 ft. and Mach Numbers of about 0.75 and given good performances with a small decrease in efficiency at the highest altitudes.

2. Their performance in clouds is not satisfactory. In the case of the axial instrument it has been shown that the element is wetted by creepage of water along the central vane. The tangential instrument does not suffer from this type of fault to the same extent but the overall effect of the vortex appears to be a cooling of the element in a cloudy air stream.

When runs are made at different speeds in layer clouds the readings are practically independent of speed but this effect appears to be due to increased evaporation at the higher speed. A traverse through a cumuliform cloud almost invariably results in a lower temperature reading within the cloud and it is not clear at present what correction should be applied in this case. Icing by blocking the inlets prevents the thermometers from functioning properly and both electrical and chemical deicing affects the readings of the instrument.

Further studies are being made but the prospect of measuring cloud temperature accurately by means of the vortex thermometer or any other thermometer which relies on the distortion of the airflow to centrifuge the droplets away from the sensing element is not good.

Meanwhile the method of using a freely exposed thermometer with its clear air heating correction multiplied by an empirical factor between about 0.7 (a value obtained in speed runs in warm stratocumulus) and unity (for ice crystal clouds) gives the best results at present. In this case readings for about 2 minutes after leaving the cloud have to be discounted while the element is drying.

Further possibilities are the use of sonic thermometers or some form of radiation thermometer but both these would involve a large development programme.

B. Vertical Currents.

The measurement of vertical currents is attempted by studying the motion of the aircraft. The most straightforward way is to fly with constant power setting and attitude through the cloud taking readings of height and airspeed. Changes of height over given time intervals are then taken to be a measure of mean vertical wind speed [*5*], some allowance being made for variation of air speed. Alternatively a method based on the integration of the aircraft's vertical acceleration as given by an accelerometer located at its centre of gravity may be used [*6*]. More elaborate methods are available in which the variation of the aircraft's forward speed and pitching angle have also been considered [*7*]. However none of these methods is entirely satisfactory as they do not take into account the inertia of the aircraft in taking up changes imposed by the vertical motions of the air. The problem of what is the resultant motion of an aircraft in unsteady conditions is very complex and the complete derivation of the air's vertical motion from the aircraft's response even more so with the result that further progress is likely to be slow.

However, tests made with the first two methods give reasonable agreement on likely magnitudes of up and down draughts. In medium sized cumuli 10—20 ft./sec. have generally been found and in large cumulonimbus up to 30—50 ft./sec. over England. This latter value may possibly be exceeded occasionally. The largest values are found in the upper half of the cloud. Typical traverses using the accelerometer method show each updraught region to be composed of several smaller cells.

C. Water Contents.

The types of instruments used by the Meteorological Research Flight to measure water content are (i) hot wire water content meters and (ii) icing rate meters.

1. Since the temperature of a heated wire in a cloudy airstream varies with air temperature wind and free water impinging on it the design is usually to have two hot wires in the instrument one of which is dry and one wet and both having the same flow over them. The output from a bridge with two wires in opposite arms will then depend only on the water content. This may be achieved by centrifuging out the droplets before they reach the second wire by means of a suitably designed housing or by mounting the two wires on the forward and rear sides of an airfoil. The limitations of this type of instruments are as follows:

a) If the wire temperature is too low a limit is reached when all the oncoming water cannot be evaporated in time.

b) At very high wire temperatures also there is no variation of output signal with water content probably due to the formation of a steam film around the wire.

c) At all wire temperatures hysteresis effects are present and different signals are produced depending on whether the water content is increasing or decreasing.

The practical result of these factors is that these types of instruments will only give accurate readings in the range from 0 to about 2 g m^3. For measurements in large cumulus clouds an extension of this range is essential. A suggested method of achieving this, which is now being studied, is to arrange that the wire temperature should always be maintained constant at rather more than 200° F with a variable and measured power input which is proportional to the amount of impinging water. It should also be mentioned in connection with design of these instruments that special devices are required for their calibration. On the surface an icing wind tunnel is necessary and at altitude it is desirable to provide some form of spray bars to calibrate the instrument before it is used in the cloud.

2. Another method of finding water content in supercooled water droplet conditions is to measure icing rate. In the instrument shown being calibrated in a wind tunnel in Fig. 4, ice forms on the edge of a disc which rotates and a feeler operating through a transducer produces a reading proportional to the thickness of the ice. Behind the feeler a scraper removes the ice and so the accumulation of ice per revolution is known and from it the water content can be worked out. An instrument of this type has a range of about 0 to 2 g/m^3. the limit being due to the release of latent heat during the phase change from water to ice [*8*]. This raises the disc temperature so that only a proportion of the water is frozen and the remainder runs off without producing an indication. To overcome this difficulty this particular instrument has its disc continually cooled by means of a liquid nitrogen supply which is adjusted to main-

tain a given disc temperature. When this is very low the instrument is also capable of measuring water contents at cloud temperature above freezing.

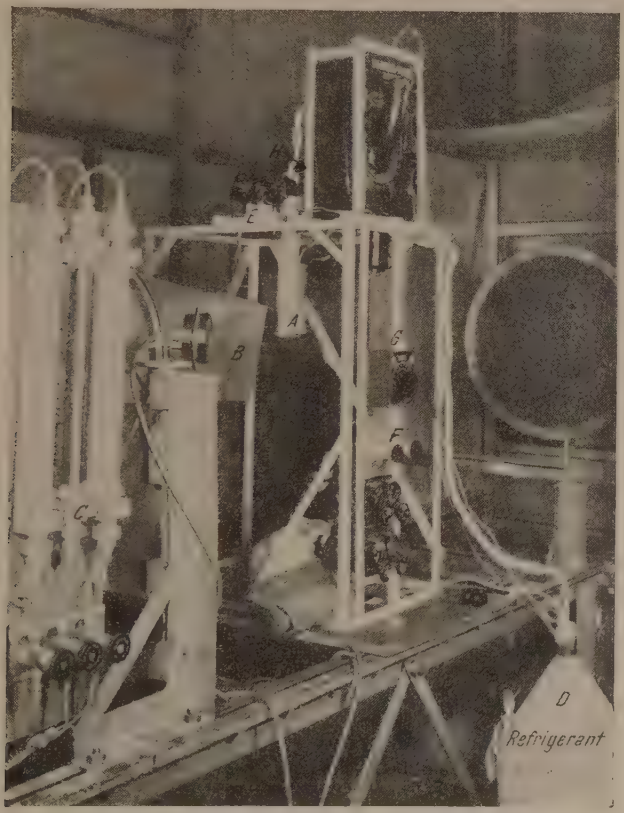

Fig. 4. Calibration of refrigerated rotating disc icing meter in a wind tunnel.
A Rotating Disc.
B Wind tunnel with variable speed and temperature.
C Tunnel water jet supply.
D Refrigerant piped to Disc.
E Disc Motor.
F Controls for refrigerant and deicing fluid supplies.
G Bridge to measure disc temperature.
H Transducer to convert ice thickness into an electrical reading is not visible on this photograph.

The maximum water contents that might be expected in a large cumulus cloud from considerations of adiabatic lift range in temperate latitudes from about 1 g/m³ in a cold winter cloud to 7 g/m³ in a warm summer cloud. As no generally accepted water content meter has yet been devised capable of measuring these higher water contents they can only be estimated at present. The highest value measured in the few flights made so far with the refrigerated disc is 3.1 g/m³ in a cumulus cloud at a height of 12.000 ft.

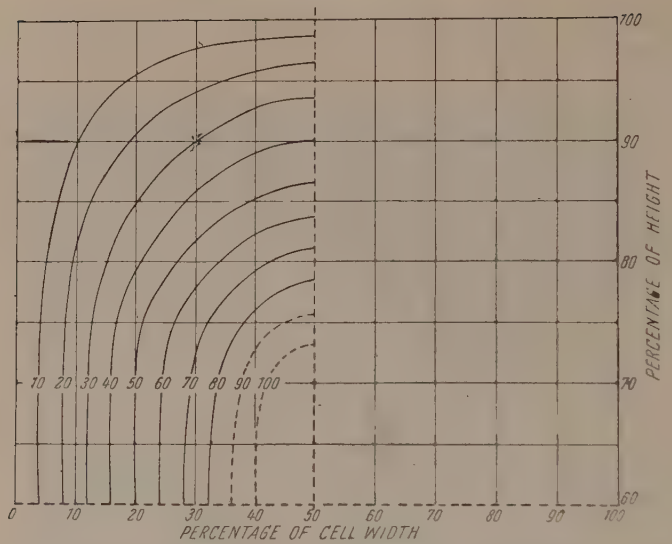

Fig. 5. Idealised distribution of water-content in a cumulus cloud expressed as a percentage of maximum realisable water-content on the assumption of adiabatic lifting.

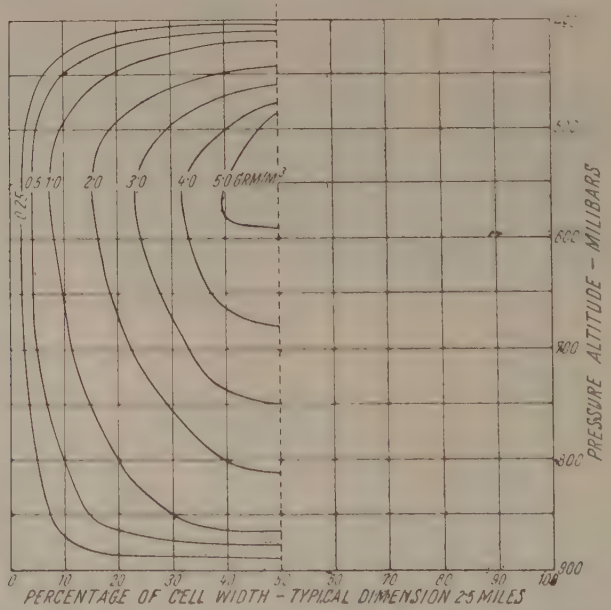
0·25 0·5 1·0 2·0 3·0 4·0 5·0 GRM/M³
0 10 20 30 40 50 60 70 80 90 100
PERCENTAGE OF CELL WIDTH - TYPICAL DIMENSION 2·5 MILES
600
800
900
PRESSURE ALTITUDE - MILIBARS

Fig. 6. Distribution of water-content to be expected in a typical cumulus cloud having base at a height of 900 mb. (3240 ft.) and a temperature of 60° F and having top at 400 mb. (23561 ft.).

In the cold base clouds values approaching the theoretical figures have been measured and in clouds of medium base temperatures the hot wire

instruments at times go off the scale for considerable periods. Fig. 5 shows the results of 10 flights with the hot wire meter in medium sized cumulus clouds in which, at the different values of percentage of cloud thickness and depth, have been plotted means of percentage of theoretically attainable water content. From this it appears that in the growing stage the theoretical value is likely to be attained in a central core up to about 70% of the total cloud height and covering perhaps one quarter of its width. A section of this type appears to be necessary in any application of entrainment ideas to cumulus cloud development. If this model is applied to a large summer cumulus cloud in temperate latitudes as in Fig. 6 the water content would attain 5 g/m^3 at about three quarters of the height of the cloud. However this appears to be approaching extreme values (apart from those increased by sedimentation effects) as, before a cloud usually reaches this altitude over England, precipitation processes by both the BERGERON and the coalescence mechanisms will be well advanced. Depletion would then follow quickly unless the updraught is very large.

D. Particle Size.

Measurement of particle size is desirable over the range from a few microns diameter to that of several millimetres diameter both in the liquid and the solid form. For the larger particles the problem of the large impact on sampling followed by the shattering of the particle has been the chief difficulty and, although several methods have been proposed, none have been satisfactory and so the quantitative sampling of hail, snow and to a lesser extent raindrops from aircraft is not yet possible. For cloud droplets however the magnesium and oiled slide techniques are in regular use although both have limitations. The former, which relies on the small droplets making craters in a surface of magnesium oxide proportional to the size of the droplet, has the advantage that the record can be microphotographed at leisure after landing. However, it is difficult to use at airspeeds of above about 140 knots, and large droplets bigger than 80—100 μ diameter and also ice crystals shatter the surface. In the oil system it is necessary to microphotograph the sample immediately after use to avoid errors due to coalescence on the slide and this is done in the aircraft. Crystals can be also caught in the oil and mixed samples obtained if care is taken to avoid melting before photographing. Otherwise, a sample which was originally crystals appears as a sample of large droplets. Similarly the effect of splash from the slide holders may cause a spurious large droplet sample. If care is taken to avoid these pitfalls the oil method can be made to measure cloud droplet sizes up to a few hundred μ diameter. Sampling at high rates can be achieved by means of suitable sampling guns; the one shown in Fig. 7 uses compressed air and is capable of taking five samples at about one second intervals.

An alternative system of crystal sampling utilising the replica method due to V. J. SCHAEFER [*11*] has had only moderate success in M. R. F. aircraft owing to the difficulty of avoiding shattering of the crystals.

Fig. 7. Cloud droplet sampling gun and camera.
1. Air supply.
2. Control valves.
3. Slide holder.
4. Photographic equipment.
The slide carrier is pushed outwards through the aircraft skin on the ramp and the slides exposed by pushing the control valves.

V. Rainfall from Non-freezing Clouds.

Probably the most important finding in recent years as regards rainfall mechanisms is that the ice-phase is frequently unnecessary in the production of rain both in the tropics and in temperate latitudes and this is amply confirmed by recent observations in England.

1. Firstly, especially in conditions of warm sector drizzle or light rainfall when the freezing level is about 10,000 feet or more, it is very common for all the clouds and rain to be below about 8,000 feet. A typical case is shown in Fig. 8. Three other definite cases were noted in September this year. The aircraft took off in rain at 10.00 h on 18. 8. 1954 and most of the ground stations in Southern England reported some rain at intervals during the morning. Rainfall amounts for the 12 daylight hours were all between a trace and 0.3 mm. The base of the cloud was at 2000 feet with temperature 60° F and highest tops 6,500 feet with temperature 44° F, the freezing level being at 10,000 feet with no cloud above. Drizzle

on the windscreen was reported by the pilot at all levels between 3,000 and 5,000 feet. This is a very common type of pilot's report in this kind of cloud and is often received when no rainfall is reported at the

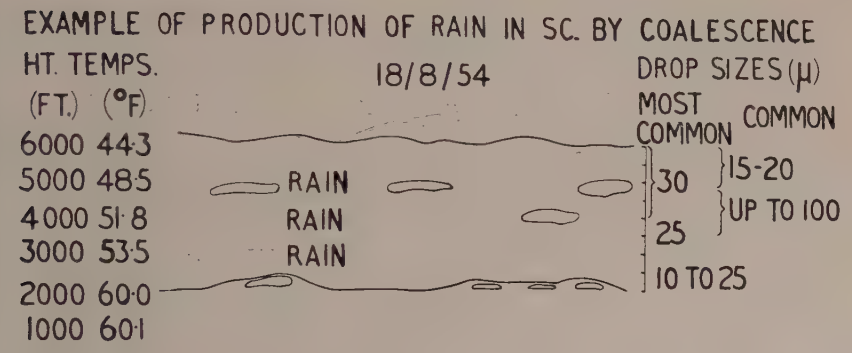

Fig. 8.

ground. In this case 10 droplet samples were taken every 500 feet through the cloud and the results are summarised:

a) The most frequent diameters were 10—15 μ near cloud base and 20—30 μ at 500 feet higher.

b) Above this 30 μ was the most common diameter but near the tops it again dropped to 15—20 μ.

c) Larger drops of 100 μ or more diameter were found at all levels and were plentiful between 3,500 and 5,000 feet, rain also being reported at these levels.

The raindrops in this and similar cases are almost always more frequent towards the top of the layer.

2. As regards cumulus clouds not extending to the freezing level they often contain some large drops but infrequently produce rainfall at the surface in England.

Our general experience with droplet sampling in many flights of this type in large and small cumulus, which also appears to be in agreement with that of [*9*] and [*10*], is as follows: —

a) Small droplets less than 10 μ diameter are found both in the base of the cloud and at all heights near the edges.

b) Droplets well inside the cloud above 1000 feet from the base have mean diameters of about 20 μ slightly increasing with height.

c) In addition to this basic spectrum a few large droplets are found with diameters of 20 μ near the base and up to 80—100 μ at 1000 feet or more above base. By 3000 feet above base 200 μ diameter drops are often found and the larger sizes increase in number at higher values of cloud thickness with a broadening of the spectrum. In clouds more than about 5000 feet depth the median volume diameter usually exceeds 50 μ.

d) Droplet populations in cloud are extremely inhomogeneous and samples taken 200 feet apart are quite different. This is especially noticeable in small cumulus where out of say 5 samples taken at these intervals one will contain a rather broad spectrum up to say 30—40 μ maximum diameters while all the remaining samples have narrow spectrums up to 10 or 15 μ maximum diameters. For some reason the larger droplets usually seem to be in groups within a comparatively small portion of the cloud. There is also a tendency for the larger drops to be found more frequently in decaying old clouds. The larger droplets appear to be more common on some days than others, and are more frequent in mixed cumulus-stratocumulus cloud situations.

e) The effective increase in droplet size with height more than offsets the increase in water content with height with the result that droplet density decreases with height.

So far no reference has been made to cloud containing ice crystals but the evidence of several flights in large cumulus clouds extending well above the freezing level is that in many cases the precipitation mechanism is well advanced before the BERGERON mechanism has time to operate. This is illustrated in Fig. 9 which illustrates the type of results obtained when an aircraft successively penetrates a large cumulus at a constant level. In this case a cumulus head projected through a Sc layer and had base at 2000 feet, tops at 12,000 feet and the traverse was made at 10,000 feet where the temperature was 20° F. Six traverses were made over a period of 37 minutes and the variation of upcurrents, water content, icing, drop sizes and crystal sizes are shown as well as cloud photographs and radar echoes. At first tops were hard in appearance and there was a radar echo and clear icing. Updraughts and mean water contents were rather small but maximum water contents exceeded the range of the meter at times.

The cloud was about 3 miles across of which 1½ miles was a well marked upcurrent and the cloud tended to spread in extent as it decayed with time. Visibility in cloud was apparently only about 20 yards or so at first but was several hundred yards by the end of the runs. Radar echoes were received in all but the last two traverses. Icing rates decreased with time and also changed from a clear to a rime type. There

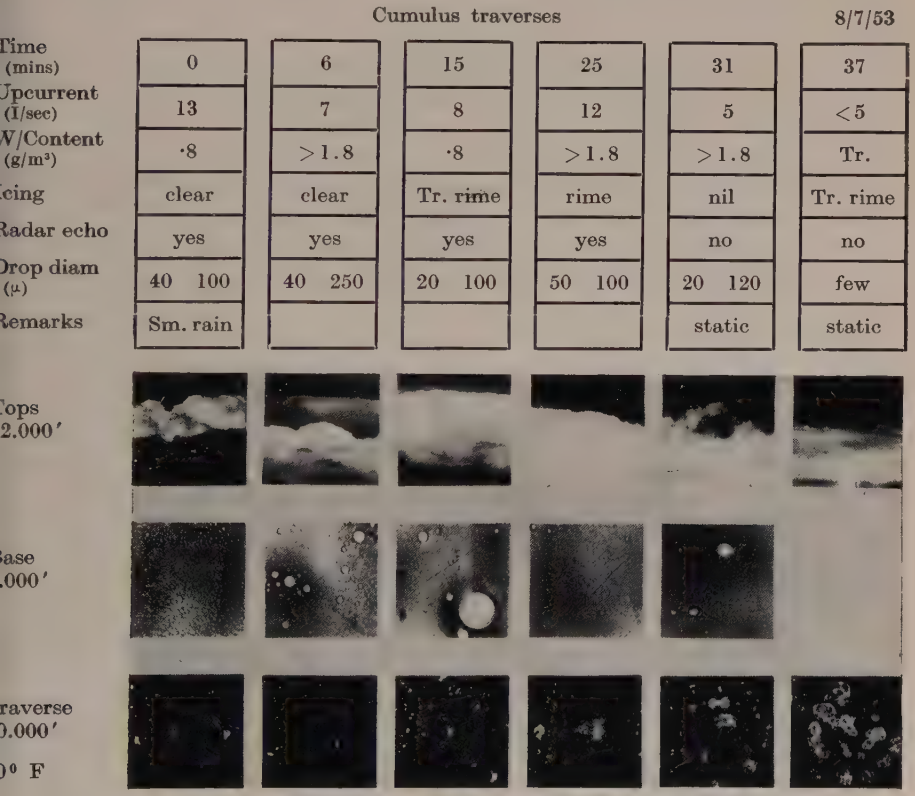

Fig. 9. Repeated constant level traverses of a cumulus cloud.

were very few ice crystals at first and these appeared to be single plates with a few columns. They did not change much for 10 minutes or so, but after 15 minutes were frequently 50 μ and occasionally 180 μ across and some showed attached droplets. It seemed as though ice crystals were present at a very early stage but needed 20 minutes or so to become effective for precipitation. Droplets of 40 μ diameter were frequent at first with occasional droplets of 100 μ or more diameter. Six minutes later diameters of 200—300 μ were observed and appeared to have dropped out to a large extent by the third run which was 15 minutes after the first. Fresh supplies of smaller droplets of 30 μ diameter seemed

to appear again in the later stages. The last oil sample shown had to be rejected on account of a melting crystal turning to droplets in the oil before it could be photographed.

The general impression from this particular flight therefore was that at the beginning drops of practically raindrop size were present and giving a radar echo. The general conversion to crystals occurred later but it seemed that a good deal of the precipitation had occurred before the crystals attained any size. In this case it seems that this cloud, which was rather warm for the BERGERON mechanism to operate, produced most of its rainfall before the crystal stage.

The diagram Fig. 10 shows the temperatures at which cloud tops are usually found in the liquid and ice phase respectively.

1. American and Canadian icing studies [*12*, *13*] give about —30° F as the lowest temperature of serious icing. However, between 10° and 0° F there is considerable decrease in the number of icing occasions. This is taken to indicate the range where supercooled droplets begin to change over to ice crystals. Other studies give —5 to —15° F as the lowest temperature of icing.

2. Studies in England [*14*] show that above 10° F droplets are usually found in cloud tops and crystals below 0° F. It should be emphasized that this is an average distribution. Crystallisation temperature appears to vary from day to day and also from place to place and it often happens over a wide area that a few tops only are glaciated while many others at the same height are still hard.

3. From a study of war time flights LUDLAM [*15*] produced the data in the lowest graph which shows the temperature for winter and summer occasions at which cumuliform clouds had hard tops indicative of droplets or wispy tops indicative of ice crystals.

On the whole therefore it seems that the average temperature at which ice crystals form in large quantities in cloud tops is between 0° F and 10° F.

4. The graphs referring to data given in [*16*] on the other hand show the incidence of rain with respect to temperature of cumuliform cloud tops. The main feature is that 50% probability of rain exists when the cloud top temperature is about 20° F and also when cloud thickness is about 7,000 feet.

Hence, from this comparison the 50% probability of rain occurs at tops temperature some 15° F higher than the 50% probability of the cloud top being composed of crystals. Combining this evidence with that given above it appears that the crystal phase does not contribute to a large proportion of the rainfall observed from convective clouds. It appears that this is also the case in rainfall from layer clouds when the freezing level is high.

The presence of large liquid drops at a comparatively early stage in cumulonimbus clouds will be an important factor in the production of hail. If further work confirms that they are usually formed early and play a major part in the rainfall process under all conditions it means

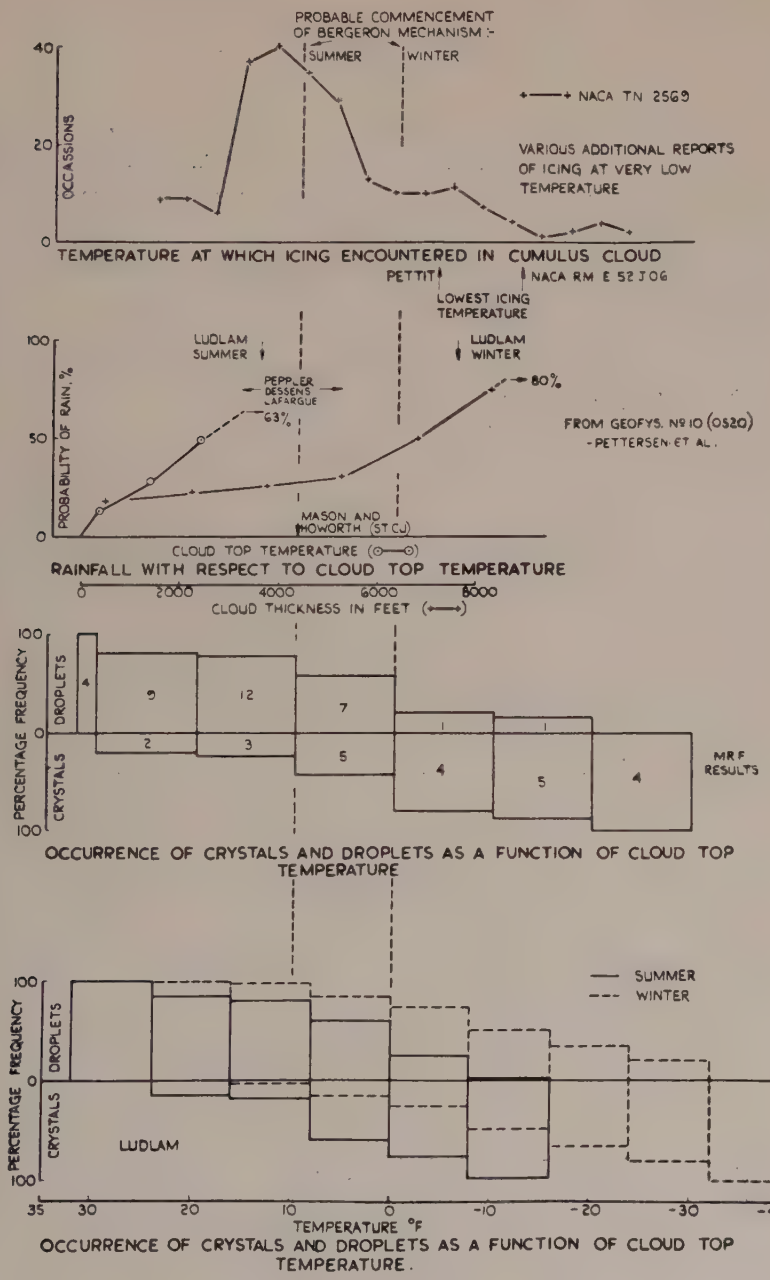
PROBABLE COMMENCEMENT OF BERGERON MECHANISM :-
SUMMER
WINTER
NACA TN 2569
VARIOUS ADDITIONAL REPORTS OF ICING AT VERY LOW TEMPERATURE
OCCASSIONS
TEMPERATURE AT WHICH ICING ENCOUNTERED IN CUMULUS CLOUD
PETTIT
NACA RM E 52 J 06
LOWEST ICING TEMPERATURE
LUDLAM SUMMER
LUDLAM WINTER
PEPPLER
DESSENS
LAFARGUE
63%
80%
FROM GEOFYS. Nº 10 (0520) - PETTERSEN ET AL.
PROBABILITY OF RAIN, %
MASON AND HOWORTH (ST CU)
CLOUD TOP TEMPERATURE
RAINFALL WITH RESPECT TO CLOUD TOP TEMPERATURE
CLOUD THICKNESS IN FEET
PERCENTAGE FREQUENCY
DROPLETS
CRYSTALS
4
9
12
7
1
1
2
3
5
4
5
4
MRF RESULTS
OCCURRENCE OF CRYSTALS AND DROPLETS AS A FUNCTION OF CLOUD TOP TEMPERATURE
SUMMER
WINTER
LUDLAM
TEMPERATURE °F
OCCURRENCE OF CRYSTALS AND DROPLETS AS A FUNCTION OF CLOUD TOP TEMPERATURE.

Fig. 10.

that cloud seeding by liquid drops or hygroscopic nuclei is not likely to achieve much general success and also that seeding by dry ice or silver iodide is considerably limited in its application.

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(The Munitalp Foundation, Inc.)

Jet Streams, Thunderstorms, and Project Skyfire.

By

Vincent J. Schaefer.

With 7 Figures.

Summary. More than 70% of forest fires in the northwestern United States are caused by lightening. The Project Skyfire is an attempt to learn more about the atmospheric conditions leading to thunderstorms in this area and to investigate the possibilities of an artificial influence on their development by cloud seeding. The experiences gained with the training of amateur observers as well as the first scientific results of the project are briefly discussed. During the first year of observations, for instance, there was found to exist an intimate relationship between a certain type of fast moving thunderstorms and the intensity and position of the jet stream. Finally, the great economical value of researches in the field of applied meteorology is stressed.

Zusammenfassung. Über 70% der Waldbrände im Nordwesten der Vereinigten Staaten werden durch Blitze entzündet. Das „Project Skyfire" hat es sich zum Ziel gesetzt, die atmosphärischen Bedingungen, welche zur Bildung von Gewittern in diesem Gebiet führen, zu untersuchen und die Möglichkeiten einer künstlichen Beeinflussung durch „seeding" zu erforschen. Die gesammelten Erfahrungen mit der Schulung von Amateur-Beobachtern, sowie die bisherigen wissenschaftlichen Ergebnisse werden kurz diskutiert. Schon im ersten Jahr der Beobachtungen ergaben sich interessante Zusammenhänge zwischen einer bestimmten Art von rasch ziehenden Gewittern und dem Jet-Stream. Schließlich wird auf den weitreichenden wirtschaftlichen Nutzen großzügiger Forschungen auf dem Gebiet der angewandten Meteorologie hingewiesen.

Résumé. Plus de 70% des incendies de forêts dans le Nord-Ouest des Etats-Unis sont dûs à la foudre. Le «Project Skyfire» a pour but d'étudier les conditions atmosphériques conduisant dans ces régions à la formation d'orages ainsi que les possibilités d'agir sur cette formation au moyen d'inséminations artificielles. On discute brièvement les expériences faites en instruisant des observateurs amateurs ainsi que les résultats scientifiques. Dès la première année de recherches, on a constaté d'intéressantes relations entre un certain type d'orages rapides et le jet stream. Enfin on attire l'attention sur le grand intérêt économique d'études étendues dans le domaine de la météorologie appliquée.

Within the past eight years experimental meteorology has developed into an entirely new aspect of meteorological science. Previous to 1946 a number of attempts were made to conduct experiments in the atmosphere, but for various reasons these efforts were not successful.

The many important technical advances which developed under the stress of World War II, typified by such developments as nuclear energy, radar, and jet aircraft, gave a tremendous impetus to the search for knowledge in many new fields of science. This resulted in many entirely new programs in basic scientific research as new principles were discovered and new problems arose.

The current interest and active research programs concerned with experimental meteorology may be traced to two short scientific papers describing laboratory studies by CWILONG [*1*] and SCHAEFER [*2*]. These independent studies in England and America described the interesting phenomenon related to the spontaneous nucleation of ice crystals in the temperature range of —35 to —40°C. In the paper by SCHAEFER, reference was made to the potential importance of the phenomenon described to the modification of supercooled clouds in the atmosphere. This was predicated on his previous studies concerned with precipitation static and aircraft icing phenomena [*3*, *4*].

On November 13, 1946, SCHAEFER flying in a small airplane successfully seeded a natural supercooled cloud in the atmosphere with a few pounds of dry ice fragments. In addition to the long snow streamers which immediately formed in this successful attempt to convert a supercooled cloud to snow, this simple experiment initiated a series of activities and controversies which have developed like a chain reaction.

The simplicity of the experiment and its implications made an appeal to the popular imagination which led to extensive activities in this field. The discovery by VONNEGUT, a co-worker of SCHAEFER'S, that silver iodide could also be used to affect supercooled clouds, and especially that effective ice crystal nuclei in tremendous quantities could be produced from simple ground based generators, gave rise to extensive cloud seeding projects in most parts of the world. The claims and counterclaims which emanated from this phase of experimental meteorology continue to grow.

In attempting to evaluate the effectiveness of cloud modification operations, much thought and energy has been expended by persons of varied qualifications. The limitations imposed by variations of the physical nature of the natural atmosphere make such efforts difficult, if not impossible, to achieve in an objective manner using the methods thus far employed.

One of the major reasons for this peculiar situation is that we do not yet know much about the processes which cause rain or snow to form in clouds. It is important to recognize several simple but important physical and chemical relationships which exist in the atmosphere. It is now recognized that there are several different physical processes which form the precipitation in rain and snow storms. In some storms a single

mechanism may be involved, while in another a combination of several may play roles of equal importance. Perhaps the most important single factor controlling the variations which occur in the formation and development of clouds is the concentration of microscopic and submicroscopic atmospheric nuclei in the air feeding into the area. Such nuclei consist of several different classes but are primarily (1) condensation nuclei — i. e., those upon which water molecules gather in a liquid state, and (2) ice crystal nuclei — those which serve as centers for ice crystal formation.

Rarely, if ever, is there a lack of condensation nuclei in the atmosphere. In air passing over thousands of miles of ocean the concentration drops to low levels but rarely less than fifty million in a cubic meter of air. Scattered among these will be a small percentage of relatively large particles [*7*]. Shortly before reaching the dew point level in the atmosphere, the salt particles in the air start growing and often lead to the development of the drizzle type and rains of moderate intensity so common in maritime areas.

Ice crystal nuclei were for a long time considered to be essential in the development of any appreciable amounts of precipitation. While the Bergeron-Findeisen theory of precipitation mechanisms is probably of considerable importance in the higher latitudes and in the development of thunderstorms and heavy shower type rainstorms, it becomes increasingly evident that rain may develop even in supercooled clouds without recourse to the development of the ice crystal phase. These findings, together with the large variations of at least a millionfold which occur in the concentration of ice crystal nuclei [*8*] and the implications of the meteoric dust theory [*9*], all point to the strong possibility that seeding mechanisms when properly understood and applied will have increasing importance in the control of atmospheric processes.

Project Skyfire.

Project Skyfire is essentially an attempt to discover new facts about the atmosphere, especially in relation to the formation of thunderstorms and certain properties of jet streams. Established in 1953 as a cooperative effort between the Division of Fire Research of the U. S. Forest Service and The Munitalp Foundation, it is based upon earlier studies made by Schaefer and Gisborne in 1948 [*10*]. Since more than 70% of the forest fires which occur in the timbered mountains of the northwestern United States are caused by lightning, it is desirable and of considerable importance to learn more about the various phenomena responsible for creating this serious problem. Among the goals of the project is the distinct possibility that as more knowledge is gained about such storms, methods may be devised for preventing or modifying the development of thunderstorms by cloud seeding techniques.

Objectives of Project Skyfire. An important feature of the current research under Project Skyfire is the development of new field methods

for observing atmospheric phenomena. This approach is directed toward an attempt to learn more about the properties of individual storms. By establishing a network of observation posts on mountain summits located so that the areas observed interlock, a cloud survey procedure has been established which should provide answers to the following questions:

1. Where do clouds first form in the area under study?
2. Do thunderstorms originate in these locations or are they fully developed when first observed?
3. If thunderstorms originate within the observation area, do they always form in the same location?
4. What are the main differences between "wet" and "dry" thunderstorms?
5. What type of thunderstorm and how much lightning occurs to produce the worst fire occurences in both number and intensity?
6. Is there a relationship between the number of cloud to ground strikes and the occurence of forest fires?
7. What are the atmospheric conditions which lead to the formation of lightning storms and may they be predicted accurately?
8. What are the general physical conditions in terms of cloud structure, height, thickness, wind field, and related factors necessary for the formation of cloud to ground lightning?
9. Is it possible to classify thunderstorms into several distinctive types and relate these to definite meteorological conditions?
10. Are there definite storm tracks followed by active thunderstorms?
11. What are the conditions which determine the degree of shear which prevents the development of lightning storms in large cumulus clouds?
12. What is the relationship of a jet stream to thunderstorm development?
13. Is it feasible to locate a jet stream using certain distinctive cloud forms?
14. Is the presence of a jet stream over an area related in any specific ways to the rapid increase of forest fire danger?
15. Are local gusty ground winds related to the presence of a jet stream?
16. When a jet stream moves into the region, does it tend to persist in a particular geographic locality?
17. Does a definite weather sequence follow the entrance of a jet stream over an area?
18. Can jet streams be detected by variations in atmospheric electrical currents?
19. Are jet streams related to fast moving lightning storms?
20. What region of the Northwest is best suited for the study of lightning storm modification by seeding methods?

Perhaps the most important question of all is whether it is feasible to obtain reliable data of the type required to answer the type of questions listed from a network of mountain stations manned by fire lookout

observers having the benefit of only a brief period of training. If it can be demonstrated that relatively untrained persons can be trained within a few days to effectively observe, record, and report significant atmospheric phenomena, such as cloud types, storm tracks, and lightning occurences, a significant advance may be made toward increasing our knowledge of atmospheric processes, especially in what may be termed "micro weather systems", i. e., the finer details of the cloud systems which develop into storms.

The Use of Mountain Summits as Cloud Observation Sites. The use of mountain top lookout stations for gathering cloud and lightning data is particularly effective. Although many such stations are occupied during only a few months of the year, the period of occupancy coincides with the occurrence of very important atmospheric phenomena.

From a mountain summit it is feasible to observe the detailed structure of cloud systems to a distance of about 25 miles, an area exceeding 1,250,000 acres. Cloud systems such as long bands of high cirrus, thunderstorms, and similar large scale phenomena may be seen for much greater distances. With good visibility the general pattern of high clouds and storms may be recognized for well over a hundred miles — an area of nearly 20 million acres. Since visibility at the station is important, it is also necessary that the mountain used for the observation site be lower than the base of the clouds. In the mountains of the northwestern United States, this cloud base level ranges between eight and ten thousand feet although it is commonly higher. In the Southwest the base of cumulus clouds ranges from twelve to sixteen thousand feet. The mountains used for Project Skyfire were in the range of 4500 feet to 7700 feet, with the exception of Mt. Washburn which was 10,317 feet, M. S. L. This latter mountain was in a drier air mass so that it was rarely in the clouds.

The Cloud Survey Network of the Northwest. The 1953 Project Skyfire cloud survey network utilized 25 mountain summits in the region north of the Salmon River in eastern Washington, Idaho, and western Montana. Based on the experience of the 1953 thunderstorm season, this network was reduced when planning for 1954 to fifteen stations plus two outlier stations in the Wallowa Mountains of eastern Oregon and the Snowy Range of northwestern Wyoming. The geographic locations of these mountains are shown in Fig. 1. Their location was determined by the experience of 1953 which indicated that an important primary source of thunderstorms resided in the Wallowa Mountains of Oregon. Any storm emanating from that area and moving with the prevailing southwesterly winds would pass across the densest part of this network and would be observed in detail. By using an isolated post like Mt. Washburn no. 17 in the northern end of Yellowstone Park, nearly 200 miles from the nearest cloud survey station, a rough check was maintained on cloud systems south of the main network.

Although Russel Mountain no. 10 in the Wallowas was within interlocking range of the major network, its main function was to watch cloud

developments over the high mountains to the west and north where the 1953 studies indicated the major source of thunderstorms crossing the area occurred. These Wallowa Mountains are flanked on the south and west by semi-arid low basins which apparently serve as extensive heat sources to trigger off cumulus clouds over the summit of the high ridges which culminate in Sacajawea Peak, 10,033 ft. M.S.L.

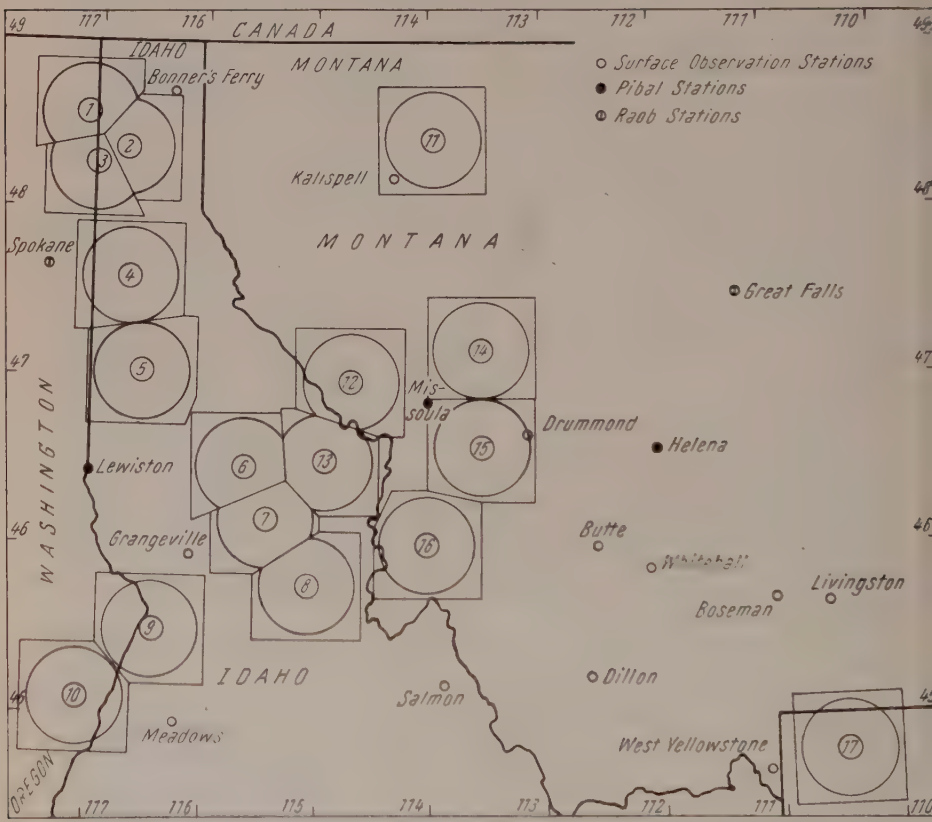

Fig. 1. Geographic locations of mountain summits used in 1954 Skyfire cloud survey.

Two 16 mm. time lapse movie cameras of the type developed by The Munitalp Foundation for cloud photography [*10*] were located in this area. The one on Russel Mountain was equipped with a 17 mm. lens and arranged to take one picture every two seconds during the development of a thunderstorm. On Cold Springs' lookout, about 40 miles away, a sphere camera was located designed to take one picture of the Wallowa Mountain area every 10 seconds. This camera covers a horizontal angle of 115°. When projected at normal speed, the time scales are exaggerated by 32 and 160 times respectively.

Gisborne Mountain in northern Idaho was established as the primary station in the cloud survey network, since it is immediately adjacent to the field headquarters of the survey and is readily available by road and FM radio.

Gisborne Mountain no. 1, North Baldy no. 2, and Stone Johnny no. 3 constituted a special triangular net for obtaining more extensive data when desired. Since they were closer together than any of the other mountains, more detailed triangulation data and related information could be obtained whenever required for special studies.

The Skyfire Cloud Survey School. For the three days starting June 28, 1954 the forest fire lookout observers attended intensive school sessions held at the Priest River Experimental Station in northern Idaho. During the week immediately before the cloud school convened, most of the observers were trained for their major job — that of spotting, locating and reporting "smokes" — the incipient indication of potential forest fires. Twenty-four persons attended the school, seven of them man and wife teams who would work together during the summer period. The school sessions consisted of six 2—3 hour periods with more than half of the time devoted to outdoor instructions at the summit of Gisborne Mountain. Nine instructors supplied by The Munitalp Foundation, the U. S. Forest Service, the U. S. Weather Bureau, and the Universities of Montana and Washington distributed the teaching load.

The students attending the cloud school possessed a wide variation of qualifications. They included high school, college and granduate students, farmers, ranchers, school teachers, college professors, etc. They came from widely scattered geographic locations ranging from homes within sight of the mountain to be occupied to places more than 3000 miles distant. They all had several characteristics in common, in particular, a love of the mountains and an active interest in natural phenomena. Because of the wide diversity of interests and personal attitudes, one of the interesting by-products of the Skyfire project will be an analysis of the relative abilities of persons of differing cultural backgrounds related to their analytical ability and effective recording of natural phenomena.

The informal attitude between instructors and students, the enthusiastic approach to the problem at hand, and the friendliness of persons having a common objective contributed a great deal to the success of the project.

The Skyfire Cloud School Program. The three days of instruction during the 1954 cloud survey school were directed toward the development of a simplified concept of atmospheric clouds and methods for identifying and typing them.

The international approach to classifying clouds into Low, Middle, and High types was followed. The main emphasis was directed toward the identification of small cumulus, towering cumulus, anvil topped cumulus, virga, rain, and lightning for the "Low" group, altocumulus, billow and wave form clouds for the "Middle" group, and cirrus and cirrocumulus clouds for the "High" group. Photographic charts had

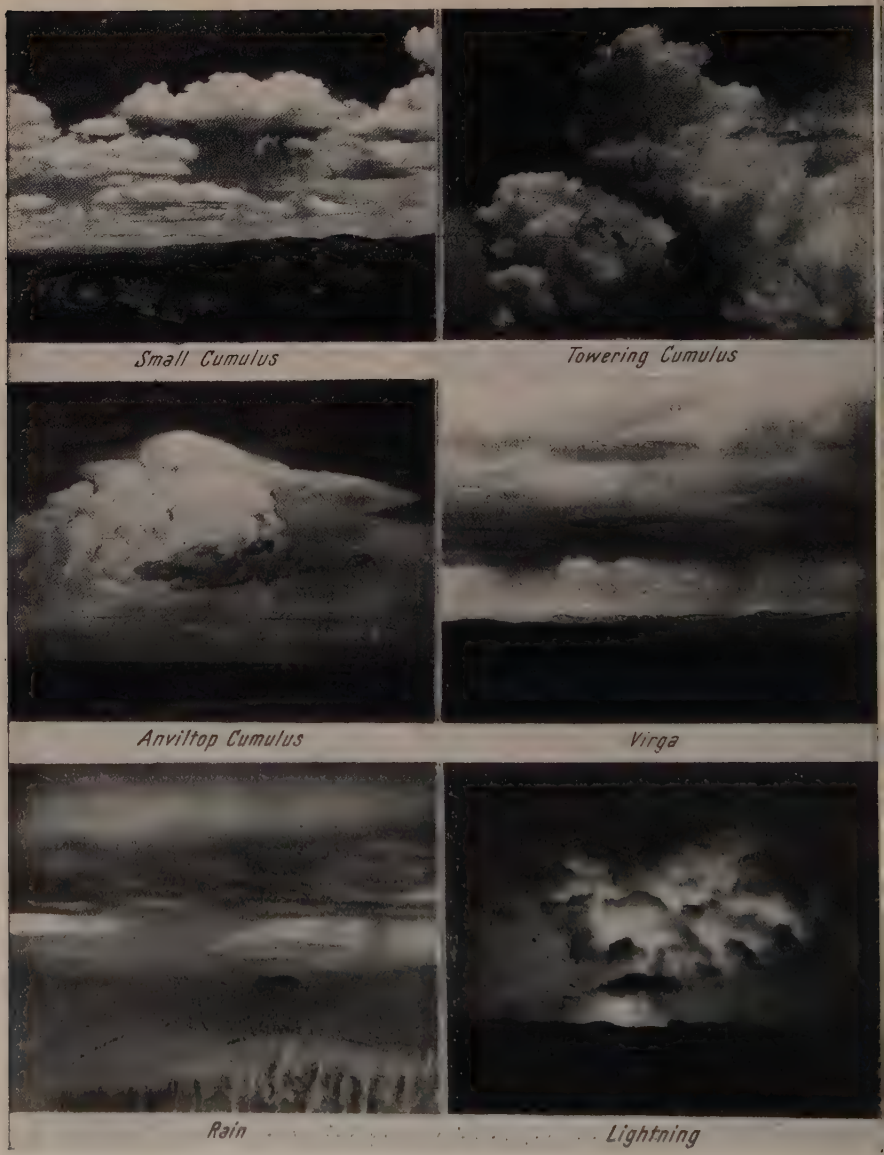

Fig. 2. Cumulus cloud types recorded by Skyfire cloud survey.

been prepared and were included in an observer's manual supplied to all who patricipated in the school. Typical examples are shown in Figs. 2 and 3.

In addition to learning how to recognize these ten basic atmospheric

Fig. 3. Middle and high cloud types recorded by Skyfire cloud survey.

features under field conditions, considerable time was devoted to instructions on methods for recording and reporting the observed information.

FORM 6
RF - INT
PREVENTION
Project Skyfire

STATION NUMBER 6
STATION NAME Hemlock Butte
DATE: DAY 15 MONTH 7 1954
OBSERVER Charles J. Brocke

INSTRUCTIONS: ALWAYS FILL IN ALL SPACES, USING A DASH "–" IF NO NUMBER OR LETTER IS APPROPRIATE. USE 0 TO DENOTE SKY CLEAR OF CLOUDS IN THE PARTICULAR CATEGORY. USE 9 TO DENOTE CLOUDS OBSCURED. A WIGGLY LINE UNDER A NUMBER MEANS THE NUMBER IS VERY QUESTIONABLE. CONSIDER 20 MILE RADIUS.

0800, 1200, & 1600 WEATHER RECORD

CUMULUS CONDITIONS

Fill in second and third lines for each observation time, as required by cumulus types and areas.

MOST ADVANCED CUMULUS TYPE
1 Cumulus
2 Towering Cu
3 Anvil tops
4 Fire
5 Rain
6 Thunderstorm

AZIMUTH (DEGREES) TO LEFT EDGE OF CUMULUS OR CUMULUS AREA

ESTIMATED VELOCITY OF CLOUD MOTION (MPH)

DIRECTION FROM WHICH CLOUDS MOVE

AZIMUTH TO RIGHT EDGE. CIRCLE IF AZIMUTHS REFER TO INDIVIDUAL CLOUD

DISTANCE (MILES) TO NEAR EDGE OF CUMULUS

SURFACE CONDITIONS

VELOCITY OF SURFACE WIND (MPH)

DIRECTION FROM WHICH SURFACE WIND BLOWS

WET BULB TEMPERATURE

DRY BULB TEMPERATURE

UPPER CLOUD CONDITIONS

HEIGHT (IN UNITS OF 1000') USED TO FIND VELOCITY. CIRCLE NUMBER IF VELOCITY IS ACCURATELY MEASURED. USE X IF VELOCITY CANNOT BE ESTIMATED.

VELOCITY AT HIGHEST CLOUD LEVEL (MPH)

DIRECTION FROM WHICH CLOUD MOVES

11 Rippled smooth Ci
12 Thin wispy Ci
13 Thick wispy Ci
14 Patterned Ci
15 Hooked Ci
16 Filaments of Ci
17 Coherent Ci
18 Straight bands of Ci
24 Liquid cloudlet Cc
25 Liquid patterned Cc
26 Decaying Cc
31 Patternless Ac
33 Rect. Ac cloudlets
34 Rect. Ac cloudlets with ice streamers
36 Ac billows
37 Coherent Ac billows
38 Ac cloudlets arranged downwind
45 Standing wave Ac
46 Moving wave Ac
47 Coherent waves of Ac

MST Time	Type	Dir	Vel	Az(L)	Az(R)	Dist	T_d	T_w	Dir	Vel	Dir	Vel.	Height	Ci	Cc	Ac	Acl
0800	0	—	—	—	—	—	61	55	SW	10	SW	50	30	10	26	30	40
0800							NOTES 0800 & EARLIER										
0800																	
1200	2	SW	10	74	106°	10	69	62	SW	6	SW	55	30	10	26	31	40
1200							NOTES 0800–1200										
1200																	
1600	2	SW	10	88	110	7	72	61	SW	9	W	70	30	13	20	31	40
1600							NOTES 1200–1600 Towering cu building to anvils in SW, E, N.										
1600																	

LIGHTNING ACTIVITY

TIME OF START (MST)	TIME OF END	NUMBER OF STROKES	AZIMUTH TO LEFT EDGE OF ACTIVITY	AZIMUTH TO RIGHT EDGE OF ACTIVITY (CIRCLE IF WITHIN 10 MILES)

SPECIAL ITEMS Note when and where rain begins. Note if lightning or thunder occurs without any rain. Note any unusual happenings (hail, severe surface wind over 30 mph, much cloud-to-cloud lightning with no strikes, odd actions of vapor trails, etc.). If rain occurs without lightning, try to measure the heights of cloud tops.

TIME	
	Lighting in northeast beyond district
	1700 – 1900

If more space is needed, use the rear of this form. On July 9, 20, 30, August 10, 20, 30, and final day of observations, on the rear write any general notes which you consider helpful (best breeding areas' distances and azimuths, storm courses, observation difficulties, etc.).

Fig. 4. Cloud survey form used in 1954 by Skyfire cloud survey.

This information was recorded on the form illustrated in Fig. 4. Using these data, the observer then learned how to prepare five simple maps

for summarizing his observations on each day. Figure 5 illustrates a set of such local maps for July 15, 1954 from Coolwater Mountain. Each of these maps is plotted on a card printed with concentric 5 mile circles

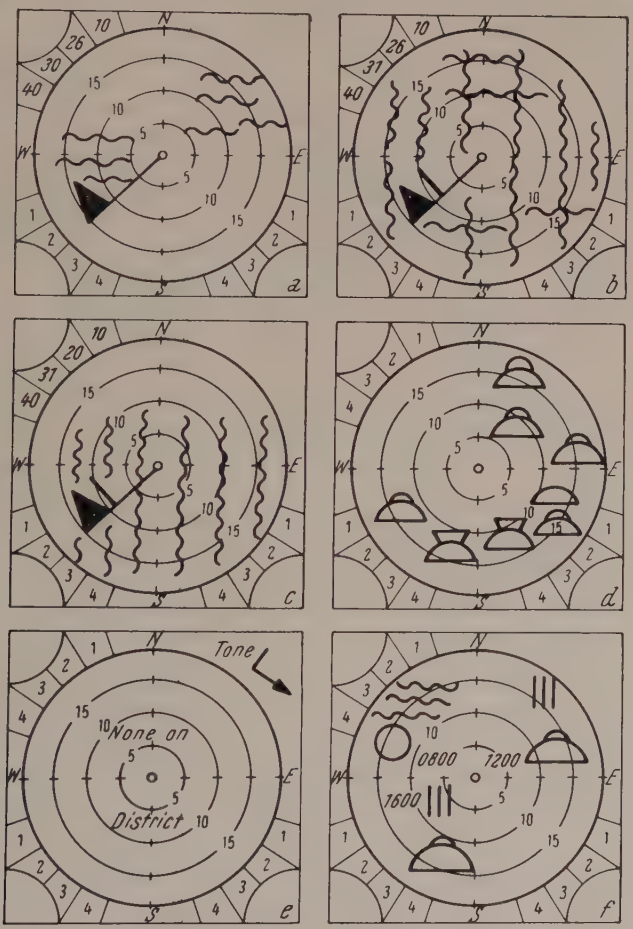

Fig. 5. Samples of cloud survey maps prepared at Hemlock Butte Lookout by Mr. and Mrs. CHARLES BROCKE on July 15, 1954. 0800 Middle and high clouds observed. 1200 Middle and high clouds observed 1600 Middle and high clouds observed. First cumulus and maximum cumulus activity during day Lightning storm activity during 24 hour period. Map drawn from information sent daily by radio.

extending to 20 miles. Figures 5a, 5b, and 5c show the Middle and High cloud pattern at 0800, 1200, and 1500 on this day. Figure 5d records the location of the first cumulus clouds observed during the early part of the day (information useful for establishing storm sources), the active regions, and maximum development of cumulus clouds during the daylight hours. Figure 5e records the presence (or absence) of lightning activity, the storm track, the approximate number of cloud to ground lightning

strokes and the period of activity. Figure 5f is a plot summarizing some of this information as reported from this station at 1700 by radio and thus received at that time in the field headquarters at Priest River and at the Regional Office of the U. S. Weather Bureau at Missoula, Montana.

In addition to having spaces for recording the data used for plotting the maps shown in Fig. 5, Form 6 also had space for recording special developments observed in the sky during the day. The manner in which this space was used served as a good indication of the interest and capabilities of the individual observer.

At Missoula a specially assigned research meteorologist from the Central Office of the U. S. Weather Bureau prepared detailed analysis of current weather patterns, especially with respect to the presence or absence of jet streams and thunderstorms over and adjacent to the area.

Relationship of High Clouds to the Presence of a Jet Stream. In addition to gathering atmospheric information directly related to the sources, formation, nature, and movement of thunderstorms, the cloud survey network had an equally important job to do in the detailed mapping of high level cloud forms.

In several papers [*12*, *13*] SCHAEFER has pointed out the apparent relationship of distinctive middle and high level cloud forms to the major core of a jet stream. Certain forms of fast moving cirrus, cirrocumulus, altocumulus wave and altocumulus billow clouds have been found to bear an intimate relationship to the location of the major axis of a jet stream. The observation of 2 or 3 of these highly distinctive cloud forms, together with their rapid movement, coherency of pattern, and persistence, was found to afford an excellent method for locating jet streams and jet streaks.

These original studies were conducted in eastern New York, U. S. A., but were subsequently extended to the North Atlantic, Scandinavia, Switzerland, the central United States, Florida, the Rocky Mountain chain, the northwestern states, and Japan. Observations from these widely scattered areas showed a remarkable similarity to a classical pattern with some local variations. One of the objectives of the high level cloud observations of the Project Skyfire network was the gathering of a body of data which might become useful in further applications of this technique for obtaining more details of this important phenomenon.

Measurements of Velocities of High Level Clouds. As a supplement to identifying and recording cloud forms a simple method was demonstrated for measuring the horizontal velocity of clouds. This utilized the Abney Level, a device for measuring vertical angles with respect to an artificial horizon. A table of cloud velocities was provided as shown in Fig. 6 which is based on the number of seconds required for a recognizable cloud element to move from one specific elevation angle to another. The accuracy and usefulness of this measurement is dependent on the estimate of the cloud height. Under most conditions, this is only roughly approximate. For simplification it was assumed that cirriform clouds were at 30,000 ft. M. S. L. and altocumulus at 20,000 ft. M. S. L. Although

wave clouds are often at fixed locations in the sky, it is often possible to measure the wind velocity producing them by noting small cloud elements passing along their outer edges. By assuming arbitrary level for the high and middle cloud forms, the indicated velocities could later be adjusted if better cloud height data were obtained from other sources.

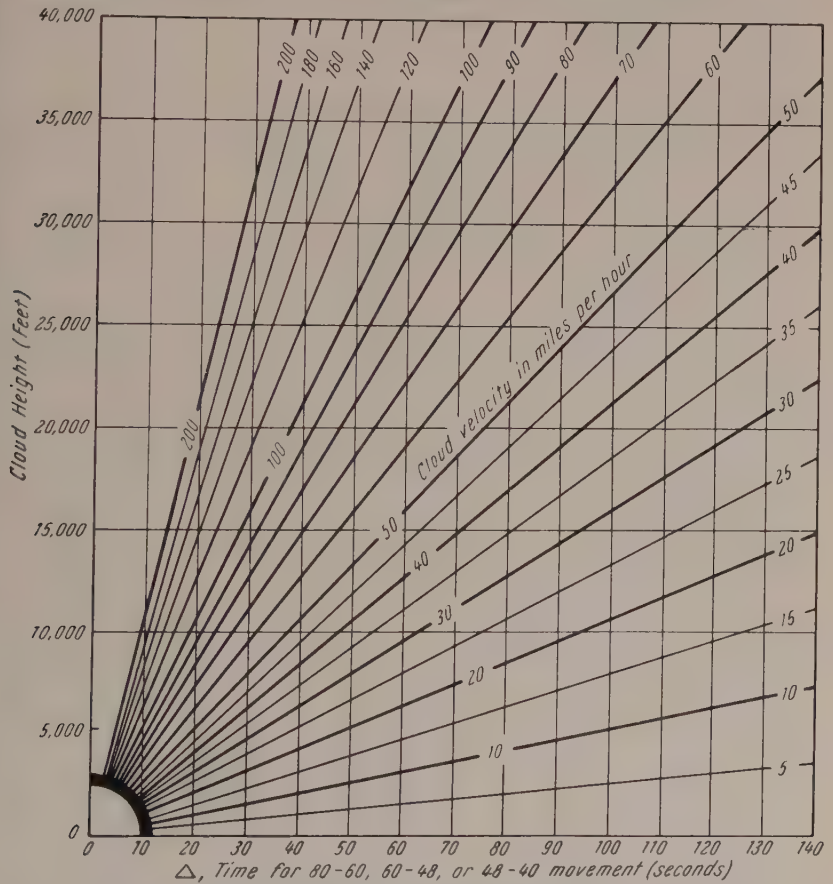

Fig. 6. Chart for determining cloud velocities using changes in elevation angle. (Prepared by PAUL B. MAC CREADY, JR., The Munitalp Foundation.)

Determination of the Height of Cumulus Cloud Bases. Another auxiliary chart shown as Fig. 7 was supplied to the lookout observers which permitted them to determine the height of the bases of cumulus clouds. This is a modification of a standard chart of the U. S. Weather Bureau and is based on the determination of the dew point from a psychrometer reading at the mountain summit, the assumption of a dry adiabatic lapse rate in the air below the cloud and that the mountain top observation is representative of the air entering the cloud base. Knowing the height of the bottom of a cumulus cloud, it is a simple trigonometric calculation

to determine the distance to the cloud and its height by making measurements of the elevation angles of base and summit.

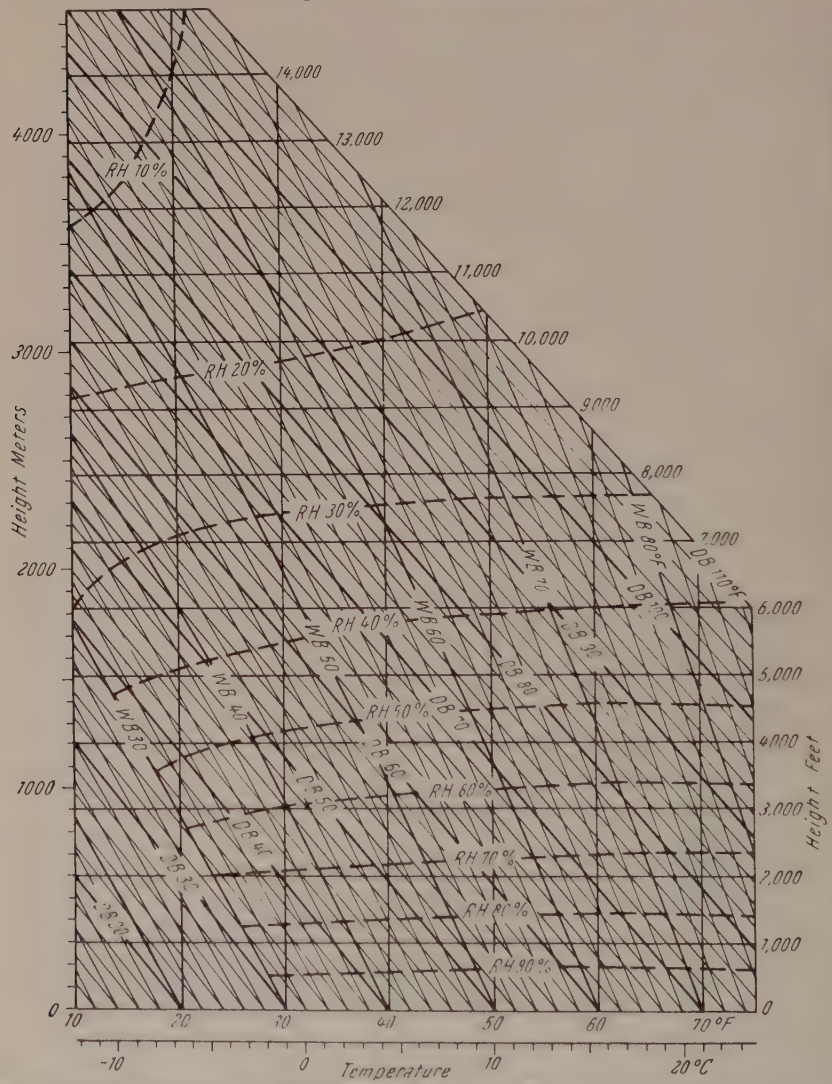

Fig. 7. Chart for determining height of cumulus cloud base. (Prepared by PAUL B. MAC CREADY, JR., The Munitalp Foundation.)

Under most conditions the location of the larger cumulus clouds could also be determined by azimuth readings from adjacent mountain lookout stations. Since practically all of the network stations were equipped with FM radio, an exchange of pertinent information along such lines could be effected in a few seconds. Standard aircraft flight maps

were supplied each observer to facilitate such triangulation procedures.

Results of the the 1953 Skyfire Program. The 1953 Skyfire cloud survey program was planned as an exploratory venture with its primary objective the development of observational procedures to determine the possibilities and limitations of using an interlocked network of mountain summits manned by relatively untrained personnel who had received brief but intensive instructions in recognizing, recording, and reporting certain aspects of atmospheric phenomena. The results of the first season were very encouraging. A preliminary study of the data obtained revealed the distinct possibility that jet stream type clouds could be used as effectively in the Northwest as in the East for adding to our knowledge of jet stream location and behavior. High gusty winds on mountain summits showed a definite relationship to the near proximity of the higher altitude jet stream maximum. A peculiar type of rapidly moving, high level thunderstorm was noted on several occasions to possess an intimate relationship to a jet stream. These fast moving storms were not like the classical air mass thunderstorm nor did they seem to be like the kind associated with frontal movements. Since this type of storm was accompanied by cloud to ground lightning of severe intensity and small amounts of rain, it represents a variety which has many peculiar properties that deserve detailed study.

Operation of the 1954 Skyfire Cloud Survey. The 1954 survey was planned to overcome various problems which developed during the 1953 survey season. Much progress was made. Simplified forms, easier methods for recording data, and a cloud observation manual were prepared prior to the 1954 school sessions.

During the school period more emphasis was placed on outdoor field sessions. In addition, a number of reels of time lapse colored cloud movies were shown, supplemented by many colored photographs of typical clouds photographed during the 1953 season over the Skyfire network.

Beginning about a week after the mountain summits were occupied, the various members of the instruction staff visited each mountain individually to clear up any aspect of the survey routine which was not adequately understood. Within the week after the school ended, daily radio reports were being received on a routine basis from the stations of the network. In addition to the daily radio report, each observer began sending in his accumulated records on a weekly basis. When received at the Missoula Research Center of the Forest Service, the individual cards for each station were affixed to the master maps. As assembled, they represent an impressive demonstration of the possibilities of this type of activity to a study of the micro-weather of a region.

Early in July a request was received from the California Range and Experiment Station of the U. S. Forest Service for information regarding Project Skyfire. At a meeting held in San Francisco with members of the Forest Service and the California State Forest Commission, plans were made to establish a lightning storm cloud survey in the mountains fo California. Representatives of the two groups visited portions of the

Skyfire network a week later, were shown the details of the procedures used, and supplied with observer's manuals and forms. By early August eight summits in the mountains of California were carrying out the cloud survey procedures of Project Skyfire.

Analysis of the Cloud Survey Data. With the assemblage of the data at the end of the forest fire season early in September, the work of analyzing the data will begin. This will be done by several groups of research workers, each interested in seeking answers to problems of special interest.

Plans are under way to prepare a cloud survey manual based on the experiences gained during the two years of observational activities.

In early August plans were formulated to continue the cloud survey activities in the Northwest through the season of 1956.

Use of Mobile Weather Observatory. Prior to the start of the 1954 cloud survey school, a mobile weather observatory reached the Priest River Experimental Station. This was constructed at the University of Washington under sponsorship of The Munitalp Foundation and designed to be a highly mobile device with its own power supply, a full complement of standard weather measuring instruments, and a number of special devices [*14*]. Among these latter units were instruments for measuring atmospheric electricity, the concentrations of condensation nuclei, salt particles, and ice crystal nuclei.

The instrumentation includes two 16 channel electrical recorders which permit the gathering of a wealth of data on any weather phenomenon which can be converted to a measurable electric signal.

All instruments are shock mounted and contained within a framework which fits into the bed of a Dodge Power Wagon supplied by the Forest Service. A 5 KW, 60 cycle electric generator driven by gasoline motor is carried in a trailer which may be detached and operated a hundred feet away from the observatory. Suitable masts and auxiliary equipment make it possible to gather integrated meteorological data of many kinds from mountain summits, active forest fires, cloud breeding spots, and other isolated locations not ordinarily available for such studies.

This unit was operated during 1954 along the Pacific Ocean, in the Priest River valley of northern Idaho, and near Missoula, Montana. The records obtained with the unit will provide material for meteorological research by graduate students in meteorology at the University of Washington and others interested in atmospheric physics.

Future Plans for Project Skyfire. During August 1954 plans were made to continue cloud survey studies in the Northwest during the 1955 and 1956 thunderstorm seasons. In addition to the gathering of information needed to answer the 20 questions listed earlier in this paper, exploratory research will be continued so as to improve upon the presently used techniques. The mobile unit will become an integral part of the network for gathering special data in the areas found to be of particular importance to the development of thunderstorms.

A cloud survey manual will be prepared which should make it possible to conduct similar studies in any part of the world.

Major emphasis of the next two years of field research will be directed toward acquiring a better understanding of the variabilities of natural thunderstorms under the differing atmospheric situations which develop over the northwestern mountains. It is of great importance that these natural variabilities be classified and understood, since it should be possible, under properly conceived and executed cloud modification programs, to produce artificially effects unlike any which occur from purely natural mechanisms.

Project Skyfire should permit us to determine the extent to which it is possible to make such classifications. Considerable reliance will have to be placed on obtaining photographic records of typical situations.

It is quite possible that subsequent studies should be made in regions where the cloud systems are less complex — in such places as Arizona, New Mexico, or southern Colorado.

Conclusions and Suggestions.

It is of great importance that considerable effort and thought be given to the establishment of atmospheric studies such as Project Skyfire on a broad and sound foundation of fact. The proper scientific understanding of lightning-caused forest fires, precipitation, and related meteorological phenomena is not of passing importance but one which will be with us as long as there are mountains, forests, winds, sunshine, and atmospheric moisture. If it becomes economically feasible to utilize experimental meteorology toward meeting some of the current problems, the advantages are so great as to justify almost any effort made at this period of our interest and understanding of these subjects.

It is of great importance that if cloud seeding operations are attempted in the near future with relation to modifying or preventing the development of thunderstorms, they be conducted with the definite understanding that such efforts are of a purely experimental nature. Since so much remains unknown in this field of experimental meteorology and atmospheric physics, it is of great importance for the future and long range success of such an important development that it should not be jeopardized by premature activities. At the same time it should be emphasized that every encouragement should be given to properly conducted experiments with thunderstorms in regions where unambiguous results may be anticipated.

To be most effective such studies should preferably be made in a region such as New Mexico where thunderstorms occur frequently but tend to be of local origin and of limited area. An ideal area for such studies appears to be in the region of Mt. Taylor west of Albuquerque. A long range experimental program based on Poject Skyfire observational techniques should be initiated in that or some similar area.

If this is done as a cooperative venture by all interested groups, many important and far reaching results may be anticipated. Cooperation and good will in such research is of paramount importance. An extension of the kind we have enjoyed in the development and operation of

Project Skyfire should result in a successful program of far reaching importance. The time is at hand when this should be carried out.

Acknowledgements.

Many persons and organizations have cooperated to establish and carry out Project Skyfire. Started in 1952 as a cooperative effort between The Munitalp Foundation and the U. S. Forest Service, a number of other groups have made substantial contributions during the past two years. It is not feasible to mention all who helped the program. Special mention should be made, however, of JACK BARROWS, GEORGE JEMISON, and REED BAILEY of the U. S. Forest Service, VERNON CRUDGE and PAUL MACCREADY of The Munitalp Foundation, PHIL CHURCH and DONALD FUQUAY of the University of Washington, WILBERT KRUMM and KENNETH NAGLER of the U. S. Weather Bureau, WELLWOOD BEALL and A. M. JOHNSTON of the Boeing Airplane Company, DEAN WILLIAMS and DONALD DRUMMOND of the University of Montana, the supervisors and rangers in Region 1 and 5 of the U. S. Forest Service, and the some sixty fire lookout observers who during the two years contributed so much to the success of the cloud survey efforts.

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(Imperial College of Science and Technology, Department of Meteorology, London.)

Planning Cloud Seeding Research.

By

F. H. Ludlam.

With 3 Figures.

Summary. It is suggested that a theory of cloud seeding needs to be developed before seeding experiments can be properly planned and assessed. This theory will arise from improved knowledge of cloud processes gained by the study of natural clouds. Some techniques used in observing shower clouds in Sweden are described, and some preliminary results mentioned.

Zusammenfassung. Es wird die Ansicht vertreten, daß eine Theorie des "Cloud seeding" entwickelt werden muß, bevor die diesbezüglichen Experimente in vorteilhafter Weise geplant und ihr Effekt abgeschätzt werden können. Diese Theorie hat sich aus einer Verbesserung unserer Kenntnisse über die Vorgänge in den Wolken durch die Ausführung entsprechender Beobachtungen in der Natur zu ergeben. Einige Verfahren, welche bei der Beobachtung von Schauerwolken in Schweden angewendet wurden, werden beschrieben und einige vorläufige Ergebnisse werden mitgeteilt.

Résumé. La nécessité de développer une théorie de l'ensemencement des nuages avant que de pouvoir projeter et analyser de telles experiences est démontrée. Cette théorie se déduira d'une connaissance améliorée de la physique des nuages, acquise par l'observation directe. Quelques procédures employées, au Suède, pour l'observation des nuages d'averses sont décrites et quelques résultats préliminaires sont mentionnés.

A. Introduction.

Much recent work in cloud physics has appropriately enough been directed towards the problem of modifying artificially clouds and precipitation. Findeisen was probably the first to propose seriously the modification of weather by cloud seeding. It is well to remember that Findeisen firmly believed that precipitation other than drizzle originates in the formation of ice crystals. When therefore he observed large cumulus with well supercooled tops which failed to yield showers, he supposed that the necessary ice crystals could not have formed. Their absence was attributed to a deficiency of natural ice nuclei, and he believed that a seeding with suitable artificial nuclei would provoke shower formation in such clouds.

Since the American discovery of methods of introducing enormous numbers of crystals into supercooled clouds, many attempts to provoke precipitation have been made on the basis of this or quite similar considerations.

Now, however, we recognize several factors besides the mere presence of ice crystals which affect shower formation, and suspect the existence of others. It is therefore not surprising that in general seedings have had inconclusive results, for the experimental conditions in which they have been carried out have never been completely specified or reproducible, nor has there been any satisfactory theory from which a definite result can be predicted. These difficulties can be overcome by making statistical tests, but in my opinion it will require many years, perhaps centuries, to discover by this method alone not merely whether and where present seeding techniques have significant effects, but also how they can be improved.

Therefore, in designing research in Sweden into the artificial modification of cloud and rain, I have assumed that we must study and improve our understanding of the physical processes which operate in cloud- and rain-systems, and reconsider how they might be influenced by suitable means. We need to determine the characteristic natural behaviour of our clouds, and to construct a theory to account for it. If then the theory still suggests that the cloud behaviour might be influenced, and if it indicates that some significant and detectable change in the behaviour will result from an artificial modification of the cloud properties, then we shall have reached the stage at which we can design and perform seeding experiments. Because of the variety and complexity of atmospheric processes, and because of the difficulty of observing them thoroughly, it may be a long time before we reach this stage. In the meantime, however, we shall be gaining new knowledge, certain to be useful if only in other connections, and accumulating information which will ultimately be needed to assess the economic importance of large-scale seeding, as distinct from the experimental seeding of individual clouds: this information is not contained in existing climatological records. The alternative course, of making a statistical evaluation of random seeding experiments, is likely to need at least an equal time and effort, with the risk of obtaining only negative results.

In the research being undertaken at the Institute of Meteorology in Stockholm University we are therefore at first concentrating upon observational and theoretical studies of clouds before attempting experiments in cloud modification. I will describe briefly some of the observational techniques we are using, and some recent results.

B. Field work in Sweden.

We are studying in particular the weather of Jämtland, in central Sweden. Two rivers, the Indalsälven and the Ljungan, flow through Jämtland, and together compose an important part of Swedish water

resources. The western and northern parts of the region are mountainous, with many peaks above 1000 m and a few to about 1600 m. The air is usually remarkably unpolluted; in good weather the visibility is almost always 100 km or more.

The field work is based at an agricultural school on a hill-top near Östersund. A fire-watching tower on a neighbouring hill, 2 km farther north, serves as a second observation place. From both places we can enjoy unrestricted views. In the eastern hemisphere the elevation of the visible horizon is almost everywhere below 0.0^0; in the western hemisphere mountains rise in several directions to angular elevations between 0.3 and 0.9^0. The nearest are the Oviks, 40—50 km to the SW, whose peaks reach up to about 1200 m and angular elevations of about 0.9^0. Between the mountains and the field stations is the large lake Storsjön, which is usually cloud-free on summer days, so that uninterrupted views are obtained of the cumulus in the mountain area, at a distance convenient for co-ordinated observations by eye, camera, radar and aircraft. Within about 10 km are a radiosonde station and an airfield suitable as a base for meteorological reconnaissance aircraft.

C. Observational techniques.

Our first studies have been mainly of cumulus clouds. There are many properties of these clouds which are important in relation to their capacity to cause showers, hail, thunderstorms, aircraft icing, and so on. Some of these properties, for example, the nature and the size distribution of the cloud particles, can be examined only by entering the cloud. The observation of these properties requires special and often elaborate equipment carried in a large aircraft; we have been obliged to leave them to a later stage in our work. In the meantime there is much to be learned from observations made outside the clouds, particularly from the simultaneous examination of individual clouds by eye and radar from the ground, and by a light aircraft equipped with simple thermometers. The aircraft we use has a ceiling of about 4 km, and is used for making detailed temperature soundings in the clear air between clouds and to confirm and supplement cloud observations made from the ground. The air observer is in radio communication with a controller-observer on the ground, who can therefore direct the aircraft to a particular cloud, which can then be studied at the same time from the air and visually and by radar from two or three places on the ground.

On the ground the control-observer is able to determine rapidly the distance and height of any cloud he sees. This is done by simultaneous measurements of azimuth and elevation from the two observing stations, using pilot-balloon theodolites. Upon selecting a cloud to be measured the controller describes to the other observer, by radio or field-telephone, the detail to be sighted, using standardized phrases, and, following the recognition of the cloud detail by the other observer, calls a signal at which the measurements are made. When some skill has been acquired

by practice the measurements can be made 20 to 30 seconds after the controller first selects a cloud.

From the two azimuth measurements the distance of the cloud from the controller is found from a polar diagram which contains arcs of circles which pass through the two observation stations, and which correspond to certain angular differences of azimuths (Fig. 1). A second diagram shows the relation between the distance, angular elevation and height of a cloud, taking into account the curvature of the earth and the normal atmospheric refraction (together these involve height-corrections which are negligible at distances of less than 30 km, but which exceed 1 km at distances greater than 130 km). In this way the distance and the height of a cloud are determined some 20 seconds after the theodolite observations, so that the complete measurement can easily be made in less than a minute. By interchanging the azimuth measurements and adding 180° to each, the polar diagram can be used to find the distance of the cloud from the second station, and thence its height above this station, to confirm that both observers in fact sighted the same cloud. (The observers also make simple sketches of the cloud which also confirm that each sighted the same detail, and which are also valuable in teaching acute observation and as a record of the kind of cloud observed). The polar diagram is also useful in allowing the controller to make a good estimate of the azimuth of a selected cloud from the second observing station, so that this can be included in his description of the cloud.

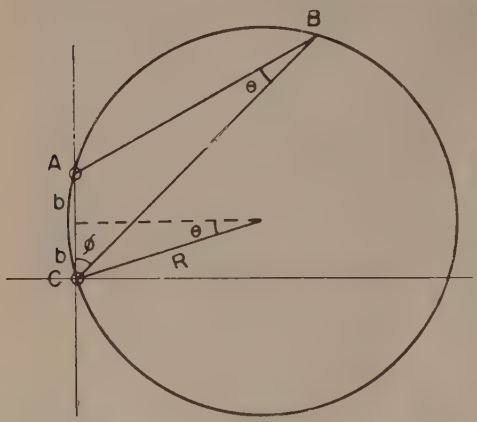

Fig. 1 Construction of diagram for determining distance of a cloud (B) from observations with theodolites at two places C and A. B lies at the intersection of CB, drawn along the observed azimuth Θ, and a circle of radius $R = V \operatorname{cosec} \Theta$, where 2 V is the length of the basis-line AC and Θ is the difference in the observed azimuth.

For the distance of just over 2 km which separates our observing stations the difference in the two azimuths amounts to 2° for clouds 40–60 km distant and in directions making angles of more than 40° with the base-line, i. e., over rather more than half of the horizon. With theodolites measuring angles to 0.1° the error in determining the distance and height of such clouds can amount to about 5%. In general the definition of cloud details permits a better estimate, and we intend in future to use theodolites indicating to 0.01°, reducing the likely error to 1 or 2%, while retaining at least the former accuracy at greater distances and in sectors of the sky extending to within 20° of the direction of the base-line. It is of course also possible to improve accuracy by increasing the length of the base-line, but only at the cost of risking

incovenience and delay in manning the second station, making communication more difficult, and reducing the ease with which the same detail of a cloud can be recognized at both stations. Our experience shows that a base-line of 2—3 km is satisfactory.

D. The observation of cumulus clouds.

Problems concerning cumulus which we are examining can be listed as follows:

a) *The formation of cumulus: prediction of cloud-base height and temperature.* Relation to temperature and humidity near the ground. Diurnal variation, and variation with topography, and in and near showers. Properties and explanation of stable layer below cumulus base-level.

b) *The growth of cumulus.* Prediction of the level of the highest tops; relation between this maximum growth and the clear-air temperature, humidity and wind distribution. Prediction of maximum updraughts; relation between rate of rise of cloud towers and their buoyancy estimated from the clear-air sounding.

c) *The properties of cumulus populations.* Determination of factors which affect the size of individual clouds; influence of rate of surface heating and large-scale vertical motions. Study of preferred regions of cumulus growth; proportion of sky at different levels occupied by growing clouds as a function of time.

d) *The formation of showers.* By the coalescence process: concentration of giant condensation nuclei near the ground. Height and temperature of cloud tops which "glaciate", give radar echoes, or showers; variation from day to day and relation to strength of updraughts, etc. Position in cloud of first radar echo, and its subsequent growth.

e) *The development of showers.* Estimate of rainfall capacity of individual shower clouds by radar. Estimate of shower rainfall over a large area by a dense raingauge network, by radar, and by river flow data. Relation to properties of cumulus population, and to the large-scale vertical motion deduced from synoptic charts. Influence of topography on shower rains.

The study of all these problems can be begun without entering the clouds. For information on the clear-air temperature and humidity we rely upon soundings made by our aircraft and by radio-sonde. The aircraft also observes the height of cumulus base and tops, but these observations are only a supplement to much more extensive observations made from the ground. We recognize, however, that when the cumulus are particularly extensive or present in complex cloud systems, on just those occasions when shower rains are likely to be intense, then observation from the ground is very restricted. For the study of such cloud systems, and those which produce steady rains, we shall need to develop our facilities for aircraft and radar observation.

In systems of scattered cumulus, however, observation from the ground can be detailed and satisfactory. Our principal interest is in

measuring the height of the cloud bases and tops, the rate of rise of cloud towers, and the stage at which "glaciation", or shower formation, occurs.

The two-theodolite technique is used for making rapid direct measurements of the height of cumulus tops, which rarely lack well-defined details. Sometimes it is possible to obtain the height of the bases by sighting on pieces of fracto-cumulus, but in general an indirect measurement has to be made. Whenever a cloud top is measured the observers also note the angular elevation of the cloud base, and from this its height is found by assuming it to lie vertically below the cloud top. Some skill is needed to choose the appropriate part of the base of a near cloud, and to choose the correct base when the cloud is distant and partly obscured by others. Usually, however, the heights deduced from the measurements of the two observers differ by not more than 50 m and agree well with direct observations from aircraft. Confirmation is also provided by measurements when the range of a shower below the cloud base is determined by radar, and when the base can be seen on the side of a mountain whose distance is known. In this way it is sometimes possible to detect a consistent variation in the height of cloud base from one part of the sky to another, or between neighbouring clouds, the differences amounting to as much as 200 m and even more when showers occur. Nevertheless in general the base-height of the cumulus at any one time appears to be uniform within 50—100 m over areas 100—200 km across, and this allows measurements of cloud-top height to be made with fair accuracy simply from single-theodolite observations of the angular elevations of base and tops. These can of course be made very rapidly, and in sectors of the sky close to the direction of the base-line, or where a two-theodolite measurement is prevented because other clouds obstruct the view of one observer. Such observations therefore form an extensive and valuable supplement to the direct measurements with two theodolites. A third diagram with a horizontally-sliding vertical height scale is used to deduce the distance of a cloud base of a given height and observed angular elevation, and the height of the tops is then read directly on the same scale. It is important to take into account in this way the effect of the earth's curvature and refraction, for the bases of distant large clouds are often observed at negative elevations.

During the course of several hours on a day of scattered cumulus up to about 50 two-theodolite measurements, and about the same number or even more single-theodolite observations, can be made, clearly defining the variation in the height of the bases and tops of the clouds. The measurements of the base-height confirm that this is usually about 200 m above the convective condensation level determined from screen-thermometers, rising as the screen-temperature increases, until the time of the afternoon maximum. Thereafter the cloud base remains at about the same height while the convective condensation level rapidly falls. The tops of large clouds are usually found at about the equilibrium level of the simple parcel theory of convection, as found on an aerological

diagram by the intersection of the clear-air sounding and a wet adiabatic drawn through the point corresponding to the cloud base. Frequently it is found that levels where many of the cumulus are checked or produce stratocumulus cumulogenitus shelves are clearly indicated by shallow stable layers on the radio-sonde record, and that this sounding appears to be representative of the conditions above the surface layers for several hours over the observation area, which extends on all sides to about 100 km from the sounding station.

E. The rate of rise of cumulus tops.

The most recent theory of cumulus growth, being developed in collaboration with SCORER and MALKUS, seeks a relation between the rate of rise of cumulus towers, their size and their buoyancy. The buoyancy is difficult to measure directly, but some progress has been made by supposing the air inside freshly emerging towers of a large cloud to have risen from near the cloud base without appreciable mixing. This assumption has received some support from direct measurements of liquid water content, made with improved apparatus by MURGATROYD in England.

The rise of individual cloud tops can be followed through a theodolite. It is necessary to observe the angular elevation of a top as soon as possible after its emergence from the main mass of cloud. The angular elevation is observed at intervals of not less than 10 seconds, from the control station, with an occasional two-theodolite measurement once the tower is clearly identifiable, to follow changes in its distance. When the cloud is observed in a direction approximately at right angles to the wind direction it is hardly necessary to consider changes in distance, and measurements from a single theodolite alone are acceptably accurate, giving the rate of rise with a maximum error of 5—10%, i. e. less than 1 m/sec. in 10 m/sec.

Equivalent measurements are made from the record of a time-lapse camera, simply by examining the changes in the ratio of the heights above the horizon of the cloud tops and base. Such films, indeed, provide more complete and valuable data than the theodolite observations, but of course cannot be evaluated at the time. We use an unusually long interval, 10 seconds, between individual exposures, since we find this to be satisfactory for making measurements, with the added advantages of economy in film and attention to the camera. Films made over several hours with a wide-angle lens give an impressive record not only of the changes in individual clouds, but of the changes in the cloud-systems, and form the only satisfactory record of the more complex skies.

F. "Glaciation".

This summer we have paid particular attention to the stage in the growth of cumulus at which the first traces of "glaciation" appear. I place this word in parentheses because although it describes a familiar appearance, it is not always certain that the process is caused by the freezing of cloud droplets.

On a typical day of convection successively larger clouds develop as the surface temperature rises. At first, as the individual towers subside they evaporate quickly and completely, but eventually the stage is reached at which the tallest towers leave more persistent fibrous trails. The development of precipitation inside the towers has now evidently progressed sufficiently to produce numbers of large particles (radii of the order of 100μ) which evaporate much more slowly than the great majority of the cloud particles (radii of the order of 10μ), and which have considerable fall-speeds, of the order of 1 m/sec. These large particles might be liquid, drizzle-size drops, or they might be large snow crystals or graupel, or the fibrous trails might contain both liquid and solid particles. However, the critical stage of shower formation has now been reached, and any further increase in the size of the clouds usually leads to the appearance of showers below their bases and the development of radar echoes. Subsequently all the largest cloud towers may be observed to "glaciate", but usually not until they have reached their maximum growth: while they are still actively rising their upper surfaces often keep the well-defined, rounded outlines typical of vigorous cumulus. A particular cloud tower has therefore to be kept under observation for at least several minutes and throughout its decay in order to establish whether the critical stage of the first glaciation has been reached, and it is important to measure the maximum level attained by the tower before its decay began. Occasionally it seems that the first glaciation occurs after several towers have risen out of the same cloud mass to about the same height. At other times the glaciation apparently occurs first in a minor tower to one side, and then spreads to the principal towers. There is no good reason to expect the first glaciations always to occur at a sharply-defined level, since the development of precipitation is controlled by several variable factors. On the other hand on any one day most of these, for example the aerosol properties and the strength of the cloud updraughts, are approximately constant, and the principal variable is the period available for particle-aggregation processes to operate inside the clouds. It may be expected that the time taken for the air of active towers to rise from near the base to the level of the cloud tops is a good measure of this period, and then the vertical extent of the clouds can be regarded as the principal variable. Indeed we find that on any particular day practically all clouds rising above a certain level become glaciated and produce radar echoes or visible showers, while smaller clouds show no traces of glaciation. The necessary thickness of cloud, and the temperature at the glaciation level vary considerable from day to day.

On 13 September 1954, for example, the glaciation level was at about 5200 m, where the temperature was —23°C (Fig. 2). On this day the convection was moderately vigorous, the upward speed of towers emerging from the cumulus being about 4 m/sec. On other days, when the convection has been weaker, the glaciation level has been lower. Sometimes it has been surprisingly low. For example, in an invasion of

polar maritime air on 31 August showers occurred over the mountains from small cumulus only 1000 m thick, at whose tops the temperature was —4°C. The highest tops observed all day were only 300 m higher, where the temperature was not below —5°C. Below the cloud base,

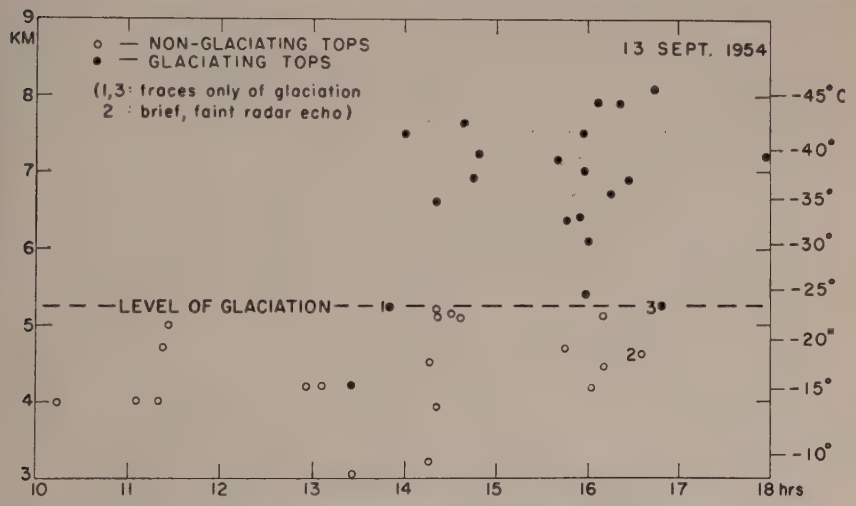

Fig. 2. Observations of maximum summit-level reached by cumulus clouds, Östersund, 13. September 1954.

which was close to the 0°C level, our aircraft observer reported "moderate to heavy" precipitation which he thought contained some snow. This impression was confirmed by reports of snow showers from mountain observing stations near Storlien, about 80 km farther west, where

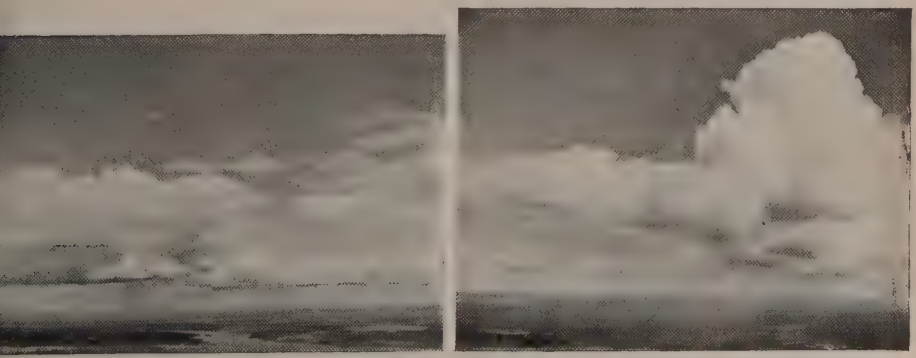

Fig. 3. Precipitating clouds with summit-level temperatures —5° C; Östersund, 20. August 1954.

the clouds could be seen to be of the same kind. Rather similar showers occurred also on 20 August from clouds with the same summit temperatures; on this occasion, however, the cloud thickness was a little over 2 km. Fig. 3 shows typical clouds with showers below the bases.

In further studies of such showers we shall need to examine the precipitation elements and the inside of the clouds to determine whether the coalescence process is important, or whether the showers are developed solely by the growth of ice crystals, even at such relatively high temperatures. At present one has a strong impression that the large-scale features of cumulus clouds exercise a much stronger control over shower formation than variations in the natural supply of condensation or freezing nuclei. This only emphasizes the need for a more critical examination of the shower clouds, and a new consideration of the possible effects of cloud seeding.

551.575.1 : 551.576.11 : 551.508.76

(Servizio Meteorologico dell'Aeronautica Militare, Roma)

Quelques appareils pour l'étude de la structure physique des brouillards et des nuages.

Par

Giorgio Fea.

Avec 5 figures.

Résumé. L'auteur décrit un appareil permettant de déterminer le contenu en eau liquide des brouillards et des nuages, dont il discute le principe thermodynamique. En plus, on décrit un tunnel placé au Monte Cimone (2164 m) qui, par sa tourelle tournante, permet d'observer et de mesurer la structure physique des nuages sous les conditions de la circulation naturelle. Enfin, on montre la construction d'une chambre à expansion qui permet d'étudier en laboratoire les différentes phases de développement des gouttelettes sous les conditions d'une expansion qui se produit d'une manière aussi lente qu'elle est observée dans la nature.

Zusammenfassung. Es wird eine Apparatur zur Bestimmung des Gehaltes von Nebeln und Wolken an flüssigem Wasser beschrieben und ihr thermodynamisches Prinzip erläutert. Sodann wird ein Windkanal beschrieben, der auf dem Monte Cimone (2164 m) aufgestellt ist und dank seinem Drehturm gestattet, die physikalische Struktur der Wolken unter den Bedingungen der natürlichen Strömung zu beobachten und zu messen. Schließlich wird die Konstruktion einer Expansionskammer entwickelt, mit der die verschiedenen Phasen der Tröpfchenentwicklung im Laboratorium untersucht werden können, und zwar unter den Bedingungen einer Expansion, die so langsam verläuft wie in der Natur.

Summary. The author describes an apparatus for the determination of the content of liquid water in fogs and clouds and discusses its thermodynamic principle. Further, a wind channel placed on Mount Cimone (2164 m) is described which, owing to a revolving turret, allows to observe and measure the physical structure of the clouds under the natural conditions of the circulation. Finally, the construction of an expansion chamber is shown, which can be used for investigating in the laboratory the different phases in the formation of droplets, this under conditions happening as slowly as in nature.

Les appareils qui vont être décrits ont été construits ou bien sont en construction pour le développement du plan de recherches établi entre le Service Météorologique de l'Aéronautique Militaire Italienne et l'Institut National Italien de Géophysique.

A) Appareil pour la mesure du contenu en eau liquide des brouillards et des nuages.

Le principe de fonctionnement de l'appareil, dont la fig. 1 donne le schéma, est le suivant: si une masse d'air m est saturée à la température T et à la pression p, avec une humidité spécifique $S = S(T, p)$ g/kg, et si, dans cette masse, une quantité d'eau liquide de x g/kg est suspendue en gouttelettes, la chaleur spécifique apparente à pression constante C_p' de la masse même sera:

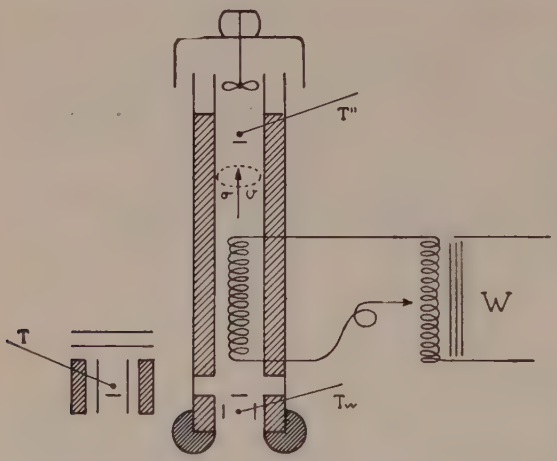

Fig. 1. Appareil pour la mesure du contenu en eau liquide.

$$C_p' \simeq C_p + \frac{S}{1000}\frac{L^2_e}{R_v T^2}$$

ou C_p est la chaleur spécifique à pression constante de l'air sec (on néglige la petite contribution de la vapeur d'eau), L_e est la chaleur latente de vaporisation à la température T et R_v la constante de la vapeur d'eau.

Si on fournit à la masse d'air en question, de l'énergie sous forme de chaleur et en quantité proportionnelle au temps, en la faisant écouler p. e. à la vitesse V dans un tube de section σ, dans lequel on a placé une résistance électrique qui dissipe une puissance W croissante en proportion du temps, la température de l'air, à la sortie du dispositif, se trouvera augmentée en raison inverse de C'_p, jusqu'à l'instant où l'eau en suspension est complètement vaporisée; après cet instant, la température croîtra en raison inverse de C_p; l'allure de la température montrera par conséquent une discontinuité à la valeur T', à laquelle la masse d'air aura été, pour ainsi dire, «séchée». On peut examiner l'allure du diagramme de la fig. 2, qui peut être comparé avec les cartes «adiabatiques» utilisées en aérologie.

Le contenu x g/kg en eau liquide sera donné par

$$x = S'(T', p) - S(T, p).$$

Toutefois une telle formule est liée à l'hypothèse d'une masse saturée sur une surface d'eau plane jusqu'à l'évaporation complète de toutes les gouttelettes.

Si par contre on considère la quantité totale de chaleur Q fournie pour porter la masse d'air de la température initiale T à la finale T'' à laquelle

toutes les gouttelettes seront sûrement vaporisées, on aura:

$$Q = m C_p \left[(T'' - T) + \frac{\overline{L_e}}{1000 C_p} x \right].$$

Ici $\overline{L_e}$ est une valeur particulière de la chaleur latente de vaporisation entre T et T'; on peut écrire alors:

$$T'' - T = \frac{Q}{m C_p} - \frac{\overline{L_e}}{1000 C_p} x = \frac{W}{J C_p \varrho \sigma V} - \frac{\overline{L_e}}{1000 C_p} x \cong A - 2{,}5\, x$$

où W/J est la puissance de la source en unités thermiques, et ϱ la densité de l'air qui s'écoule à la vitesse moyenne V dans le tube de section σ.

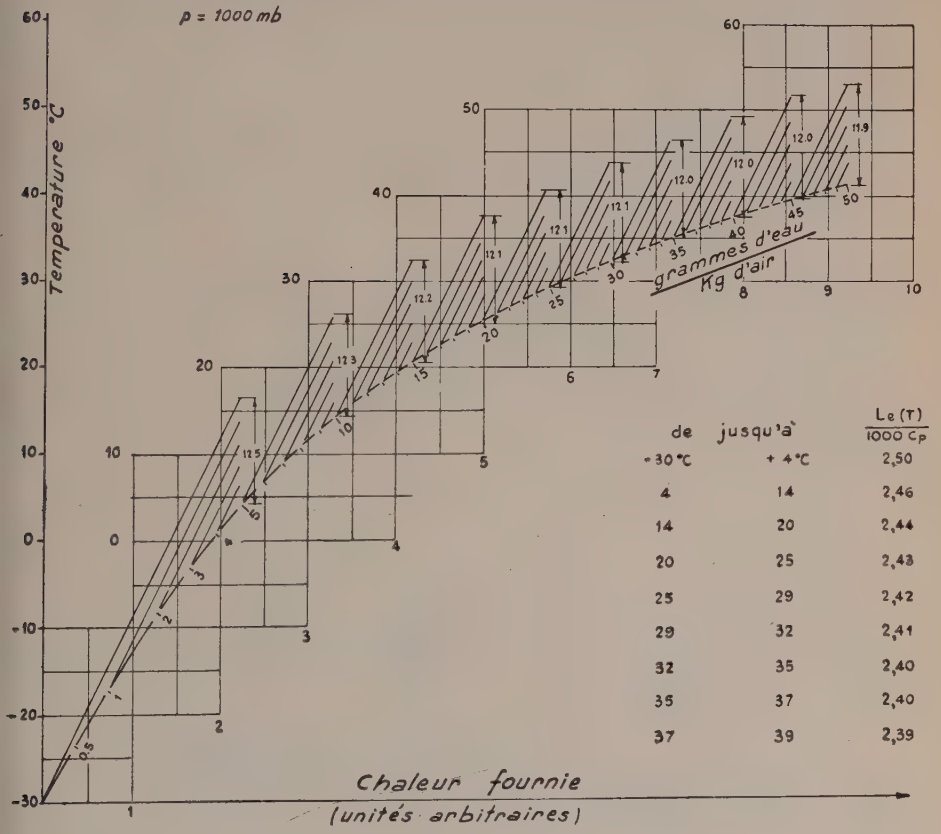

Fig. 2.

La valeur $A = \frac{W}{J C_p \varrho \sigma V}$ est caractéristique pour l'instrument et la précision de la mesure est surtout fonction de la constance de cette valeur (en particulier de la puissance fournie et de la vitesse de circulation); cette valeur peut être déterminée directement en calculant la différence $T''-T$, l'air étant dépourvu de gouttelettes en suspension.

On peut constater que la différence entre T'' par air «sec», et T'' par air contenant des gouttelettes, divisée par 2,5 (ou par la valeur plus exacte donnée dans la petite table à droite du graphique de la fig. 2) donne la valeur approximative du contenu en eau liquide en gr/kg.

Des thermomètres indiquant le 0,1° C, permettront en théorie d'avoir une précision de 0,04 g/kg, tandis qu'au sol, où ϱ est de l'ordre de 1 kg/m³, la puissance demandée est d'un watt environ pour chaque degré de différence entre T'' et T (pour air «sec») et par litre/seconde de portée.

Dans le schéma de fig. 1, T indique un thermomètre bien protégé contre le rayonnement et très peu ventilé, de façon que les gouttelettes ne s'y déposent pas; tandis que le thermomètre T_w, inséré dans la bouche d'entrée de l'air et mouillé par les gouttelettes, peut être utilisé, en combinaison avec T, pour déterminer l'humidité relative, comme dans le psychromètre classique, ce qui peut donner une indication sur l'état d'équilibre thermodynamique du brouillard ou des nuages. Avec des thermocouples ou bien des thermisteurs l'appareil peut devenir enregistreur.

Quelques possibilités de mesure du contenu d'eau par évaporation ont été discutées par BEMIS [*1*] et par MIDDLETON et SPILHAUS [*2*].

B) Tunnel à circulation naturelle.

Pour l'étude des particules constituant les nuages à l'aide de microphotographies directes, de phénomènes de diffraction, polarisation, transmission etc. on a placé au sommet du Monte Cimone, à 2164 mètres d'altitude, près de l'observatoire de Météorologie de l'Aeronautique Militaire, une tourelle tournante avec un petit tunnel orientable selon la direction

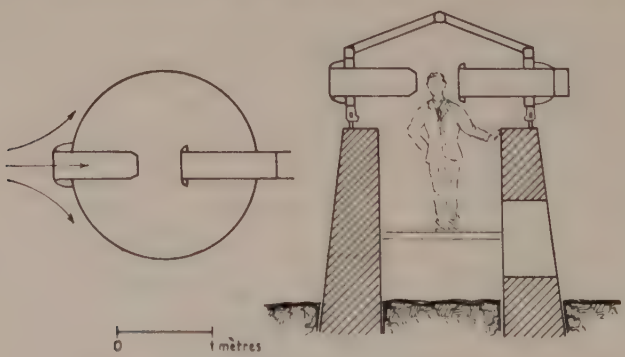

Fig. 3. Tunnel à circulation naturelle (Monte Cimone).

du vent (qui est souvent très fort); la fig. 3 en donne les coupes horizontale et verticale. La fig. 4 qui montre l'horizon théorique du Monte Cimone, peut renseigner sur les possibilités de l'observatoire.

Ce tunnel permet d'observer et de faire tout type de mesure sans pratiquement troubler la structure physique des nuages qui très souvent couvrent le sommet; la montagne est assez haute et isolée de telle sorte

que la plupart des ces observations peuvent être considerées comme faites dans l'atmosphère libre. En particulier l'installation va être équipée avec un microscope tournant dans le but de suivre les particules dans leur mouvement d'entraînement par le vent, pendant les fractions de seconde

Fig. 4. Horizon du Monte Cimone (2164 m).

de durée d'un éclair électronique. Le but essentiel du dispositif est d'étudier l'effet de la nucléation artificielle sur les nuages et sur les formations de glace.

C) Chambre à expansion adiabatique ralentie.

On a développé le projet d'un appareil de dimensions remarquables, dont la partie mécanique essentielle a déjà été construite. Son but est de permettre l'examen en laboratoire des différentes phases de développement et d'évolution des gouttelettes jusqu'à leur solidification, et l'action éventuelle de particules artificielles, dans des conditions les plus rapprochées que possible de celles qui se produisent en nature. La fig. 5 donne une idée de cette installation.

Pour la réalisation de ce but on agira sur la masse d'air au moyen d'un refroidissement adiabatique aussi lent qu'on l'observe en nature, c'est à dire de la durée d'un quart d'heure environ.

L'adiabaticité vraie des expansions sera obtenue avec un refroidissement progressif extérieur des parois de la chambre cylindrique en acier (dimensions: diamètre 40 cm, hauteur 80 cm) dans laquelle l'air va se détendre sous l'action d'une pompe. Le refroidissement des parois sera produit par circulation d'air refroidi à la neige carbonique, contrôlée au moyen de thermocouples très rapides, de façon que les parois mêmes se trouvent toujours à la même température que le centre de la chambre.

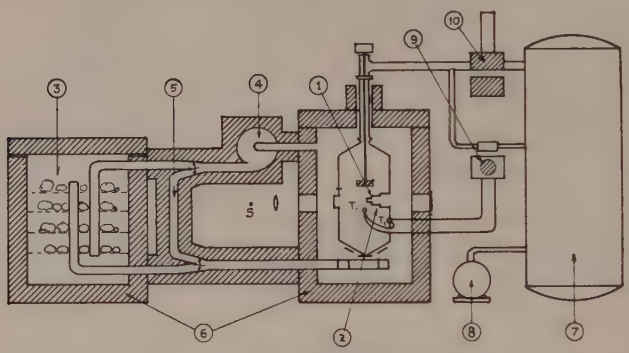

Fig. 5. Chambre à expansion adiabatique lente. 1 chambre d'observation, 2 microscope, 3 réservoirs à neige carbonique, 4 pompe de circulation pour l'air refroidi, 5 une sorte de «shunt» aérodynamique pour le contrôle de la vitesse de refroidissement, 6 isolation thermique, 7 réservoir à vide, 8 pompe à vide, 9 soupape de réglage de l'expansion lente contrôlée par les thermocouples T_1 et T_2, 10 soupapes pour l'expansion ou la compression rapides.

De cette façon les mouvements tourbillonaires devraient être empêchés, de sorte que les échanges d'air et de vapeur entre la partie centrale et celle de la periphérie pourraient se vérifier seulement par diffusion, c'est à dire très lentement. On est en train d'arranger les optiques et les circuits de thermocontrôle.

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551.577.5:551.509.67

(North American Weather Consultants)

Methods and Results of Large Scale Applications of Cloud Seeding in the Western United States.

By

Eugene Bollay.

With 8 Figures.

Summary. During the period 1950—1954, North American Weather Consultants, an applied meteorological consulting group, conducted a number of cloud seeding programs in the Western United States. Over 50,000 hours of silver iodide generator operation were recorded, which is probably one of the largest massive applications of cloud seeding on record. Methods and results of these operations are presented.

Zusammenfassung. Während der Jahre 1950—54 haben die „North American Weather Consultants", eine Gruppe von Beratern für angewandte Meteorologie, im Westen der Vereinigten Staaten eine Reihe von „Cloud seeding"-Programmen durchgeführt. Während mehr als 50.000 Stunden wurde die Wirkungsweise von Silberjodid-Generatoren beobachtet, vermutlich eine der umfangreichsten Anwendungen dieser Methode, die je durchgeführt wurden. Methodik und Ergebnisse dieser Arbeiten werden in der vorliegenden Arbeit behandelt.

Résumé. Pendant les années 1950/54, les «North American Weather Consulttants», groupe d'experts de météorologie appliquée, ont exécuté dans l'Ouest des Etats-Unis une série d'essais d'insémination de nuages. On a observé pendant plus de 50.000 heures l'effet de générateurs à l'iodure d'argent; il s'agit probablement d'une des plus vastes applications du procédé. La présente note traite des méthodes employées et des résultats obtenus.

I. Introduction.

In July 1946, V. J. Schaefer performed an historic experiment in demonstrating that dry ice (CO_2) and water droplets in a deep freeze cause the rapid development of ice crystals and that in the absence of dry ice and other substances, water droplets can be lowered to temperatures as low as —39° C without freezing. This experiment and the further efforts and results of Langmuir and Schaefer of the General Electric Laboratories, working under the sponsorship of Project Cirrus, provided

the impetus to cloud physics and weather modification in the United States which has since resulted in many active cloud physics research projects in educational centers as well as in the formation of industrial meteorological consulting groups engaged in cloud seeding.

The importance of increased precipitation and, as a consequence, water supply to the agricultural growth and industrial expansion is of vital interest to the United States. Arid and semi-arid land totals more than one-third of the total area of the United States, approximately 700,000,000 acres. Of these, only 21,000,000 acres are now under irrigation. It is estimated that during the interval 1950—1975 the production of food due to continued population growth in the United States must be increased by 20%. The problem of providing the irrigation water for this increased growth emphasizes the national importance of an adequate water supply, of which the basic constituent is precipitation.

In a recent study [2], the effect of a 10% precipitation increase on dryfarm lands was made for North Dakota, South Dakota, and Nebraska. The results of this study indicated that the per acre value of dry-farm lands would be increased by about 50%. Small increases in precipitation can produce highly significant economic benefits in dry-farming regions.

The same study also analyzed the effect of a 10% increase in precipitation to an irrigated farm area (150,000 acres) such as is typical of the San Joaquin Valley in Central California. In a normal year the resultant streamflow would be increased by 15% due to a 10% increase in precipitation which, in turn, would permit 10% additional lands to be brought under irrigation. In the case under study, this was about 15,000 acres whose farm income would amount to about $ 1,250,000 per year.

The hydro-electric utilities [3] are equally aware of the economic benefits which may be achieved by cloud seeding. The greatest potential in this regard is the possibility of minimizing departures from the normal seasonal variation in precipitation and streamflow. These fluctuations are the major factors determining the extent of utilization and capacity of a hydro-electric plant and set the ratio of balance between hydro-electric and steam capacity in any one system.

North American Weather Consultants was formed in 1950. From its inception it has been most active in the cloud seeding field. The original basis for this organization lay in the conviction of the organizers, based upon General Electric's Project Cirrus reports and on considerable personal experience in cloud seeding that *cloud seeding can increase precipitation*. The case was presented to prospective clients in the light that although there existed controversy on this matter and that there were no positive assurances of success, the economic benefits to be derived by even small precipitation increases made the taking of a calculated risk attractive. We feel results to date have verified the initial viewpoint to the fullest extent. Our activities can be viewed as industrially-sponsored research in cloud seeding, with particular attention focused on the particular problems of the client.

This arrangement had its advantages and its disadvantages. Although more support can be engendered by concentrating on the clients' special problems, the commitments thus assumed may conflict with the scientific design of an experiment directed toward isolating the effects of cloud seeding. However, it is interesting to observe what substantial results have been obtained as a result of this compromise arrangement. This organization felt in no position to engage in a running controversy over cloud seeding, nor to attempt to confirm or refute the bewildering succession of "theories" submitted by certain entrenched elements of the meteorological profession in the United States, each purporting to explain why cloud seeding would *not* produce economically significant increases in precipitation. Rather the task was set to compile data on a series of massive seeding trials conducted over the years in the expectation that the accumulated facts would eventually provide the answers needed. During the past four years, over 50,000 hours of silver iodide generator operations have been recorded for these experimental programs.

Our approach to this problem was clinical in nature. We decided that, initially, all clouds extending in height above the -5^0 level would be seeded over the target area. Precipitation in this area would then be compared with climatologically similar and adjacent areas where it was known that no artificial seeding was in progress. These areas we refer to as control areas. In the medical profession this method of evaluation to check the validity of a new vaccine or serum is common and, in fact, the analogy is strikingly comparable to this problem.

The clinical approach proved fortuitous from an evaluation standpoint because only meager information is available of the nature and characteristics of individual clouds. The precipitation data on file in the climatological archives is collected on a time basis which integrates the effectiveness of all clouds passing a certain point and does not reflect the efficiency of any individual cloud system.

Inadequate information is available on the distribution and variation of sublimation or freezing nuclei in cloud systems except that evidence suggests that at low altitude there is a deficiency of ice-forming nuclei, indicated by the presence of supercooled cloud droplets. Our approach was, therefore, to provide an abundance of highly active, artificial nuclei, effective at relatively low altitudes.

At very high levels and very low temperatures there is an abundance of ice-forming nuclei. In summer thunderstorms, the abundance at extremely high levels is so great as to constitute natural overseeding. The cirrus clouds thus formed spread out, and through shading, repress further convection.

From SCHAEFER's experiments we knew that dry ice would generate ice nuclei; however, the method of delivery of these crystals to the cloud system appeared uneconomical in contrast to the release of silver iodide crystals from the ground. Many other substances can also serve as nucleating agents, but the virtue of silver iodide is that it becomes active as a freezing nuclei at the highest temperature — in the vicinity

of —5°C. Table 1 shows the temperature — activity relationship of different freezing nuclei as listed by C. L. HOSLER [4]. The choice of silver iodide seems rather obvious.

Table 1.

List of substances tested and found active in freezing supercooled clouds.

Substance	Crystal Form	Method of Dispersal	Temp. at which Active (Degrees C)	
			Partial	Complete
AgI	Hexagonal	Vapor	— 3	— 4
$AgNO_3$	Rhombic	Vapor and Spray	— 3	— 4
Ag_2S	Cubic-rhombic	Vapor	— 4	— 5
PbI_2	Hexagonal	Vapor	— 4	— 5
NH_4I	Cubic	Vapor and Spray	— 9	—12
Cu_2I_2	Cubic	Vapor	— 9	—12
I_2	Rhombic	Vapor	—12	—15
NaI	Cubic-monoclinic	Vapor and Spray	—13	—16
KI	Cubic	Vapor	—13	—16
TlI	Rhombic-cubic	Vapor	—13	—17
$HgCl_2$	Rhombic	Vapor	—14	—17
CdI_2	Hexagonal	Vapor	—15	—18
PbO	Tetragonal-rhombic	Vapor	—16	—19
O_3	—	A.C. Spark Discharge	—14	—20
HgI_2	Tetragonal	Vapor	—18	—21
Sunlight (uncertain)	—	Trough Open Window	(—16)?	?
$PbCl_2$	Rhombic	Vapor	—18	?
$CuSO_4$	Triclinic	Vapor	—20	?
HgO	Rhombic	Vapor	—22	?

Silver iodide smoke can be produced in a number of different ways. According to the General Electric Project Cirrus Report, the most effective method for producing large numbers of silver iodide particles and achieving a fair degree of particle size control is to introduce a spray of silver iodide, acetone solution into a hot flame such as propane, with the flame passing immediately into the surrounding colder air where it is quenched. Concentrations as high as 15% with respect to silver iodide have been used by our organization, although with the techniques which we have developed, much less concentrated solutions are found to produce more significant results. Such silver iodide generators have been constructed for ground installations, portable truck installation, and for aircraft use, and are shown in Figure 1.

The effectiveness of silver iodide smoke serving as freezing nuclei is still under active investigation. From our experience the temperature of the flame is very critical in determining the size of silver iodide crystals formed. With regard to the decay of the nucleating powers of the smoke particles, there are conflicting claims on this matter. A variety of photolytic decay rates were found [5, 6, 7, 8] and later BIRSTEIN [9] presumably reconciled some of the differences by discovering a previously overlooked dependence of decay upon humidity. However, all of these findings are in

question as a result of the work of BOLTON and QURESHI [*10*] who find temperatures to be the major controlling factor. According to their data, a ten-fold decay occurs in a thirty-minute period at a temperature near 30° C and in proportionately longer time intervals with lower temperatures.

BOLTON and QURESHI's data indicate rather clearly that silver iodide, if used from ground generators at temperatures in the vicinity of 15° C or higher, to be effective must be released very close to the target area. To seed massively before convection sets in or at some great distance from the target area seems completely futile from the ground when air temperatures are much above 15° C. In contrast, at low temperatures the decay rate is insignificant and therefore seeding should be effective.

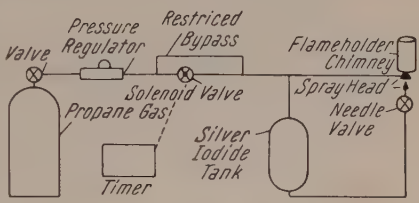


Fig. 1. Silver iodide generator used by North American Weather Consultants for ground installations. Schematic diagram of generator (above).

Of course, in addition to the natural decay of silver iodide smoke particles as ice-forming nuclei, we have to consider the diffusion of the silver iodide smoke as it leaves the generator. Little is known concerning diffusion of aerosols under unstable air mass conditions over distances in excess of a few miles. Experiments in New Mexico [*11*] with a ground—based generator emitting zinc sulfide particles revealed a rough pattern wherein the plume spread laterally to a width of 15 miles at about 30 miles downwind of the generator site. In a general way these findings correspond with the observations of seeding-modified cloud structures and precipitation patterns.

Cloud seeding with silver iodide smoke is normally conducted under unstable air mass conditions and it is to be expected, and is so observed, that some smoke reaches cloud top level within a distance of 5 or 10 miles downwind of the generator. Particles were detected, in the above mentioned field tests in New Mexico, 5000 feet above ground level at 8 miles distance downwind. This is a matter of some 20 minutes downwind, corresponding to a mean ascension rate of 250 feet per minute. From our own observations, 30 minutes is the order of the time interval critical in our seeding operations and, therefore, the source strength and diffusion of silver iodide in this time period is of special interest.

If we define the layer of artificial nucleation (L. A. N.) as the atmospheric stratum bounded at the bottom by the level at which artificial

nuclei become effective, and at the top by the level at which natural nuclei are sufficiently numerous and effective for complete nucleation, then we have under discussion a layer which may extend from the —5° C level to about the —15° C level, a thickness of around 5000 feet. In the case where the technical objective is to increase precipitation, the problem is to provide in this layer an optimum concentration of artificial nuclei when it is occupied by supercooled cloud droplets. A generally accepted value for optimum nucleant concentrations is 10^3 to 10^4 particles per m^3 [*12*]. On the other hand, complete overseeding, therefore no growth of precipitation elements and consequent reduction in precipitation, would occur with concentrations about a thousand times as great, or $10^6/m^3$ to $10^7/m^3$. This range in numbers provides the engineering limits of silver iodide smoke for the industrial cloud seeding programs.

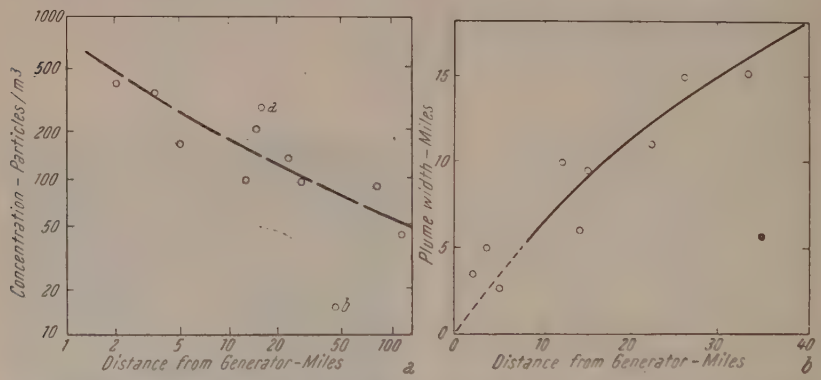


Fig. 2. Average particle concentration, corrected to 25 miles per hour wind (a) and plume width (b).

According to the curves appearing in the BRAHAM et al paper, copies of which appear in Figures 2a and b, a mean concentration of about 200 particles per cubic meter and a peak concentration of 500 P/m³ occurred at 10 miles downwind. The source strength used was 3×10^{10} particles per second. Applying this to silver iodide, a source strength of 10^{11} per second to 10^{12} per second would be required to provide 10^3 to 10^4 P/m³ at a distance of about 10 miles from the generator. Complete overseeding would occur with a source of strength 10^{14} per second to 10^{15} per second. Of course, these computations can be accurate only to the nearest order of magnitude because of lack of sufficient diffusion data collected under turbulent and unstable conditions.

Calibrations of our silver iodide generator indicates an output of about 10^{12} ice-forming nuclei per second, at a burning rate of 0.1 gram of silver iodide per minute.

II. Method of Seeding.

In a commercial operation, silver iodide generators are placed in a network in and surrounding the target area. The effective area for each

generator of our type is on the order of 15 to 30 miles wide and 30 to 50 miles downwind. A typical generator network is shown in Figure 3 and pertains to Santa Barbara County in Southern California.

The area involved in Santa Barbara County is approximately 1,756,800 acres. A total of 15 silver iodide generators have been installed for this operation. This includes an airborne generator and one portable truck unit. The aircraft generator is used for seeding clouds off the coast of Santa Barbara County prior to their on-shore flow. For similar reasons, generators have also been installed on one of the Channel Islands. The entire generator network is connected into a communications system centered at the field headquarters at the Santa Barbara Airport.

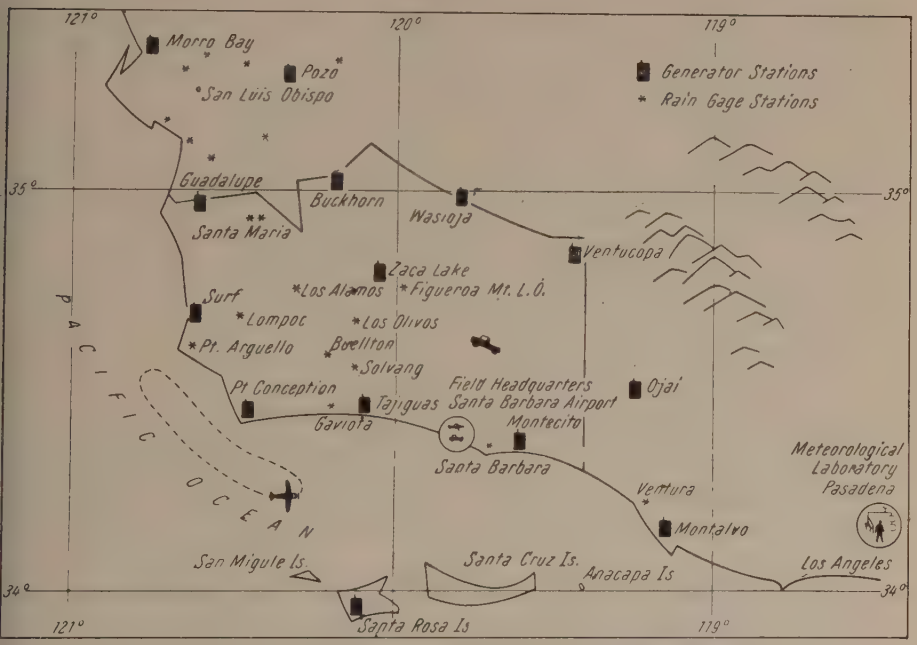


Fig. 3. Generator network for Santa Barbara project, California.

These generators are controlled by a meteorologist. His studies of the local synoptic situation in conjunction with telephoned advices from a meteorological office form the basis for the generator operation.

Of particular interest to the meteorologist are the prevailing upper air wind conditions, the temperature stratification and the height of the —5° C level. These factors determine which of the AgI generators in the network to operate. In the event that a storm is expected to produce heavy rainfall in the target area, cloud seeding operations are suspended.

During this last year, radar was also included as a meteorological tool. Whereas the synoptic weather charts give the large scale meteo-

rological features, radar can be used to locate the intense convection cells within cloud systems. In addition, the effectiveness of the seeding can be traced by watching the development of the line of showers downwind of the silver iodide generator sites, which are seen from time to time by eye, but are more often masked. Radar can also see through the enveloping cloud forms and discern the more intense convection cells as they approach and pass the target area. The radar used for this effort is a converted APQ —13, 3 cm set, mounted on the back of a truck.

III. Evaluation of Cloud Seeding Results.

The cloud seeding evaluation technique in most common use at present involves a comparison of the precipitation which fell within a seeded target area to that which fell in some control area. The control area must lie close enough to the target area so that there is natural correlation between precipitation in the two areas. The two areas must, however, be far enough apart to insure that there is no carry-over effect of the seeding from target to control area. It is desirable to use a control area which lies upwind from the target area. The comparison may be made between daily, monthly, or seasonal precipitation totals.

In this method, an excess of precipitation over the expected value may occur in the target area and yet no credit be given to the cloud seeding for this excess. The excess has to be great enough to be termed "statistically significant". It has been found that if there is not a high correlation between the target and control area precipitation, i. e. if they do not fluctuate closely together from season to season, or year to year, then the method is incapable of acknowledging increases, the increments to be expected from seeding. Also, it is important that the historical precipitation records be as long as possible. It is not always possible to satisfy all of these requirements in evaluating the results of individual cloud seeding projects, and in such cases the results from a statistical viewpoint are inconclusive.

During 1951 the California Legislature provided $ 50,000 to the California State Water Resources Board for an investigation of "the control of rainfall by artificial means". The State Water Recourses Board utilized this fund by conducting an investigation of the effectiveness of actual experimental and commercial weather modification programs in progress in California. This investigation [*13*] by the State of California was conducted primarily through a contract with the Statistical Laboratory of the University of California under the direction of Dr. Jerzy NEYMAN. After a critical analysis by this group of the weather modification evaluation reports available, they presented an objective method of evaluation which they believe avoids some of the difficulties of previous studies.

This modified method was utilized in evaluating cloud seeding operations for three separate areas in California, namely: the Carrizo Plain, an intermediate plateau about 60 miles west of Bakersfield,

California; the Southern Sierra Project, encompassing the valley floor watersheds of the Tule and Kern Rivers in the San Joaquin Valley; and Santa Barbara County on the Pacific Coast in Southern California.

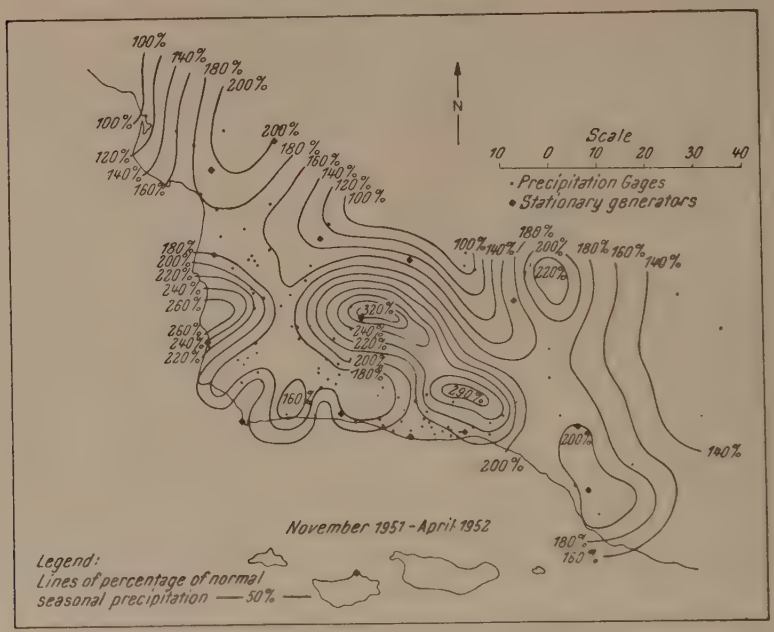
Since our group, North American Weather Consultants, conducted cloud seeding operations for three years, 1950—1953, in the Santa Barbara area, one of the operations studied, this independent and critical evaluation of our efforts by the State of California bears special attention and its results are quoted herein.

In general, the method of evaluation consisted of a comparison of the rainfall in the target area with simultaneous rainfall in adjacent areas assumed to be unaffected by the cloud seeding program. The relationship between precipitation in the two areas was determined by plotting on graph paper the square roots of the amounts of precipitation for a large number of storms occurring during the years when no seeding was in progress. The points representing the seeded storms were then plotted in a like manner and superimposed. A statistical test was then made, testing whether the variation was greater than might be expected. The square root of the precipitation amounts are plotted because by this means the Statistical Laboratory of the University of California hoped that the relative variance of the target amounts from expectation would remain constant. An additional refinement was made by dividing the storms into categories or types and by dividing the area into six target areas, namely:

Target	*Precipitation Station*
Number	Number
1. Upper Santa Ynez Basin	1. Gibraltar Dam
	2. Juneal Dam
	3. Los Prietos Ranger Station
2. Middle Santa Ynez Basin	4. Santa Ynez
3. Western Basins	5. Lompoc White Hills
	6. Los Alamos
	7. Santa Maria Weather Bureau Airport
4. South Coast Basin	8. San Marcos Pass
	9. Santa Barbara
	10. Santa Barbara CAA Airport
5. Cuyama Valley	11. Cuyama Post Office
	12. Cuyama Ranger Station
	13. Wasioja Forbes Ranch
6. Sisquoc Basin	No Precipitation Stations

The results of this study of the seeded storms are tabulated below as quoted in the Water Resources Report.

Base Map. Santa Barbara Project. North American Weather Consultants. Santa Barbara Airport. California.



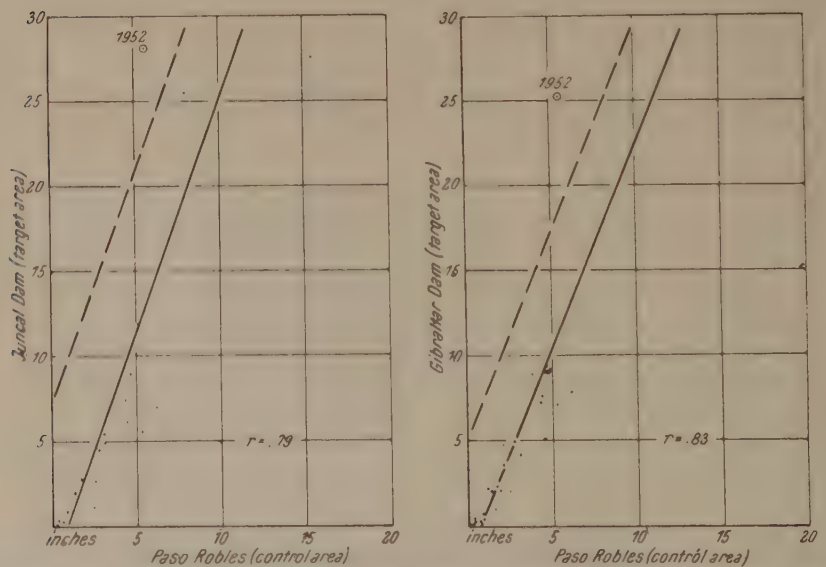


Fig. 4. Precipitation comparisons-Santa Barbara project, California. Comparison of target area to control area, January precipitation for period of record.

Santa Barbara County Cloud Seeding Evaluation — Apparent Excess of Actual Precipitation Over Expectation of Storms of Intermediate Classes, By Target Areas

Target	Storm Class Designation	Number of Storms in Program	Probability that Excess was Real	Total Precip. Excess in inches/station	Percent of Excess over Expectation
Storms actually seeded:					
1	B	22	0.99	8.46	64
2	D	33	0.999	7.80	95
3	Ie'—IIb	37	0.999	8.01	70
4	B	22	0.97	5.82	49
5	B	22	0.99	3.34	79

While the above data may not constitute documentary evidence from a statistical viewpoint, the analysis does indicate, from an engineering viewpoint that significant increases in precipitation were produced in Santa Barbara County as a result of cloud seeding. Figure 4 shows precipitation comparisons utilizing the regression method for the Santa Barbara area as used in our evaluation studies. In our industrial operations we do not have the funds to conduct such elaborate and expensive evaluations as is possible with tax money. However, we do conduct engineering-type evaluation programs for most of our operations utilizing primarily the regression method described earlier.

1. San Diego.
2. Southern California Edison.
3. Santa Barbara.
4. Tillamook.
5. Washington Water Power.
6. California Oregon Power.
7. Antelope Valley.
8. Northwest Kansas.
9. Southeast Wyoming.
10. Northeast Wyoming.
11. Tri-Counties.
12. Miles City.
13. Pacific Gas & Electric.

Fig. 5. Cloud seeding projects conducted by North American Weather Consultants.

The following table lists the cloud seeding programs completed or in progress by this organization during the last four years. Figure 5 shows the location of these areas.

Area	*Year*	*Purpose*
City of Santa Barbara and Montecito WaterAgency	1950—1951	To increase domestic water supply
Santa Barbara County	1952—1953	To increase domestic water supply and agriculture
City of San Diego	1951	To increase domestic water supply
Tillamook Burn Area	1951	To control forest fire
Antelope Valley Project, California	1951—1952	To increase rain in dry-farming area
Western Kansas	1952	To increase rain in dry-farming areas
Wyoming — three areas	1952	To increase rain in dry-farming areas
Tri-Counties, Oregon	1953	To increase rain in dry-farming areas
Montana, Custer County	1953	To increase rain in dry-farming areas
Central Sierra Project, California	1950—1955	To provide increased snowpack for hydro-electric power
Bitterroot Mountain Project	1951—1955	To provide increased streamflow for hydro-electric power
Southern Cascades, Oregon	1952—1955	To provide increased snowpack for spring runoff for hydro-electric power
Projects in Central and Northern California	1952—1955	To provide increased snowpack for hydro-electric power

The purpose of these programs can be classified into three categories, namely:

a) To increase domestic water supply,
b) To provide increased rainfall in dry-farming areas for irrigation,
c) To provide increased snowpack and streamflow for hydro-electric purposes.

It may be of interest to analyze these projects in greater detail.

1. Santa Barbara Program.

In the case of the Santa Barbara project, which has already been mentioned previously, approximately 1500 generator hours were recorded, and up to 15 generators were used in this area. This operation was conducted primarily to increase the domestic water supply and to provide additional precipitation for agricultural purposes. The results of this operation have previously been listed, as released by the Water Resources Board of the State of California. These results indicate increases between 49% and 95% for different areas within the target area.

Base Map, Northwest Oregon Tillamook Burn Project, Prepared by North American Weather Consultants, August 11 to October 2, 1951.

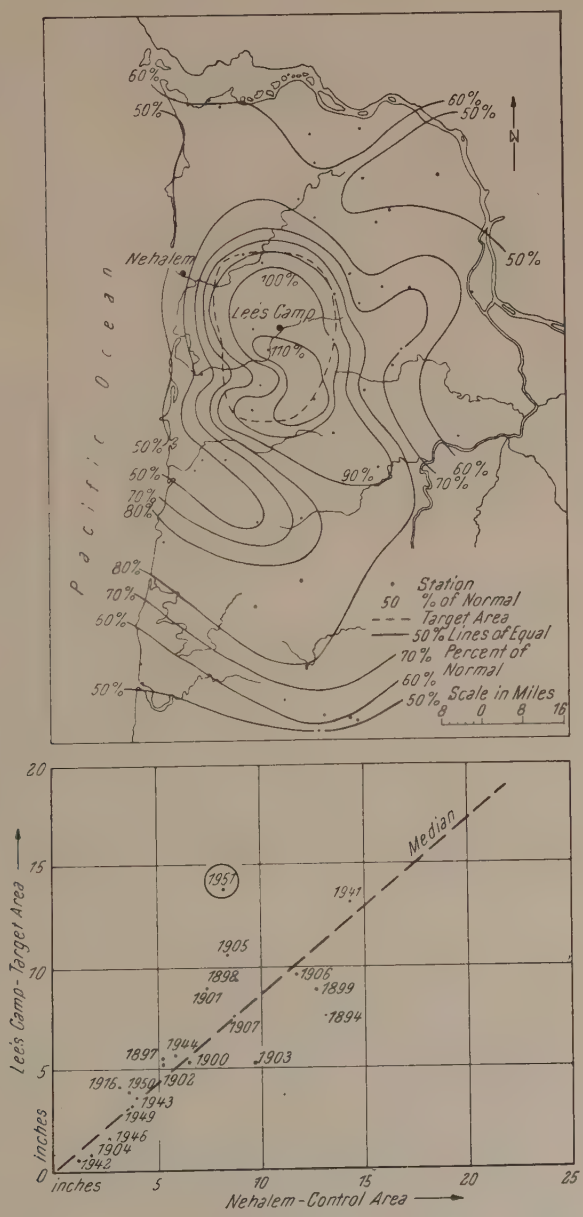


Fig. 6. Cloud seeding results Tillamook Burn Area, Oregon.

2. San Diego Program.

During the spring of 1951, for a period of three months, cloud seeding operations were conducted for the City of San Diego. Four silver iodide generators were used and operated for a total of 467 hours for the three month period, February through April, 1951. In this project, there were indications that precipitation was increased by as much as 60% in parts of the watershed area during the three month period. One of the long-record rainfall stations in the target area, Cuyamaca, has a rainfall record extending as far back as 1889. The precipitation of this station was compared with that of San Diego which was on the edge of the target area. This average ratio was 4.25; during the seeded period it was 7.41. This value was never attained in any year from 1900 to 1950.

3. Tillamook Burn Area.

A very unusual cloud seeding program was conducted during August 1951 to October 1951. In the Tillamook Burn area of Tillamook County, Oregon, forest fires were in progress and were endangering logging operations. One of the logging companies contracted with our organization to attempt to increase precipitation in order to reduce the fire hazzard. The target area included approximately 700 square miles. Five silver iodide generators were used for a total of 323 hours of operation. One major storm was seeded which occurred during the period September 28 and October 2 with unusual success. During this storm period it is estimated that over 10 inches of precipitation fell over the entire Tillamook Burn. In the climatologically homogeneous areas adjacent to the target area, similar amounts occurred only in one or two isolated spots. Figure 6 shows the results of this operation. The deviations for the total precipitation in the Tillamook Burn area ranged from a minimum of 28% to a maximum of 60% above the mode. The highest deviations found in the adjacent areas unaffected by cloud seeding was at Valsetz, with a deviation of 31% above the mode. Our conclusions were that cloud seeding did increase precipitation between 28% and 60%.

4. Western Kansas.

During the period of April 1952 through October 1952, an extensive area comprising 3,460,000 acres in Northwestern Kansas was involved in an agricultural cloud seeding program. During this period 30 generators were used for a total of 9600 generator hours of operation. From an analysis of the percentage of normal charts, it was concluded that during the seeded period the target area received approximately 84% of normal precipitation in contrast to about 69% of the adjacent control areas. This suggests that cloud seeding may have contributed to a 15% increase. In this particular case, the 15% increase is comparable to 2.06 inches of water.

5. Wyoming Projects.

Three extensive farm areas conducted cloud seeding operations in the eastern portion of Wyoming during the period April 15, 1952 to October 15, 1952. The evaluation indicated that an increase of about 10% was produced as a result of cloud seeding. The increases claimed were obtained by a comparison of percental of normal charts.

6. Oregon Tri-County Area Program.

During the period of September 1952 through June 1953, a cloud seeding program was conducted for Sherman, Gilliam, and Morrow Counties in Oregon. An evaluation of this project was conducted by the Oregon Agricultural Experiment Station and the Oregon Agricultural Research Foundation [*14*]. Cloud seeding projects have been in progress in this area for three years and have been evaluated by the same organization. The evaluation techniques have been constantly improved to the point where it is now claimed that if the average daily target precipitation is increased by 25% or more for three consecutive years, then the effectiveness can be stated with a 95% confidence limit. Neither our results nor the results of the two previous operations satisfied these criteria. From our analysis, however, it appeared reasonable that an increase of 17% had occurred.

7. Custer County, Montana.

During the period May 1953 to June 1953, an area of approximately 70 miles by 70 miles in East Central Montana arranged for a cloud seeding program. Ten silver iodide generators were operated for a total of 790 hours. The primary crop raised in this area is wheat. The results of this operation are shown in Figure 7. It should be noted that the seeded period in 1953 is far above the regression curve with an indicated increase of 86%. The probability of this value occurring by chance is .01.

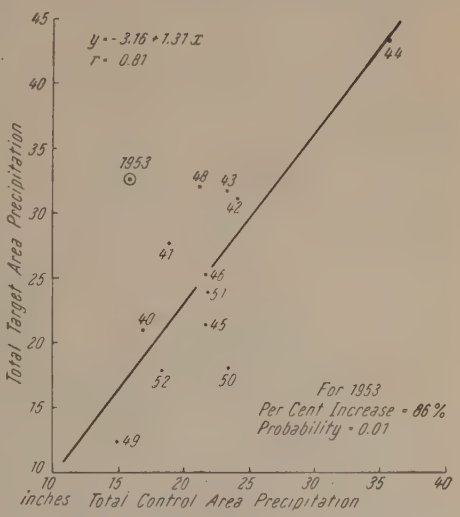


Fig. 7. Cloud seeding results Custer County, Montana. Scatter diagram comparisons for May through August.

8. Central Sierra Project, California.

This program is on a continuing basis and has been active since January 1951 in the upper drainage area of the San Joaquin River in California. The objective was primarily to increase the snowpack during the winter

months for subsequent use in a hydro-electric program. A total of nine silver iodide generators are now used for this project and a total of about 6000 hours of silver iodide generator operations have been recorded. Figure 8a and b show the comparison of the water content of the snowpack between target and control areas and summarizes the results achieved

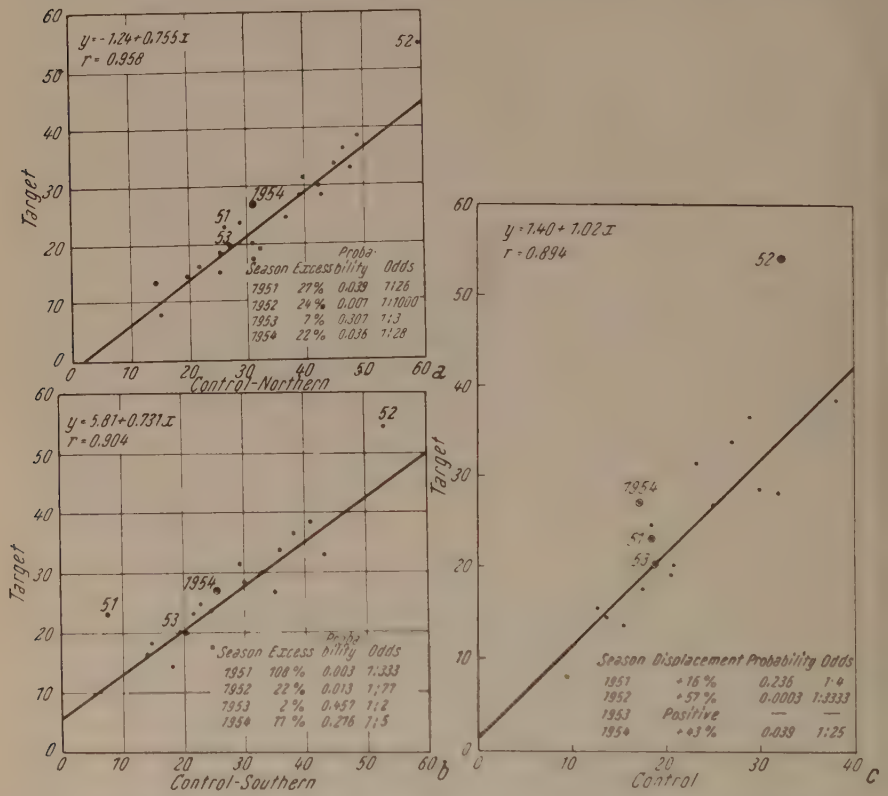


Fig. 8. Precipitation relationship: Central Sierra Project, California.
a) and b) Water content of snowpack, April first, c) Comparison of target to valley precipitation.

during four years of operations. It should be noted that in 1953 no significant increase was produced, but that in 1954 positive excesses were again obtained. Figure 8c also shows a comparison of the water content of the snowpack correlated to San Joaquin Valley precipitation stations.

9. Projects in Central and Northern California.

Three other projects in Central and Northern California have been active during the last few years. A comparison of the measured amount of precipitation from January to April 1954 over the target area Crane Valley and the control area Lower Elevations shows the following values:

excess = 45%, probability = 0,0088, odds = 1; 114, the regression equation y = 2,89 + 2,73 x, and r = 0,935. From a comparison of precipitation over the target area Strawberry Pinecrest to the northwestern and southwestern control area we found: excess = 38%, probability = 0,042, odds = 1 : 24, the regression equation y = —4,61 + 1,62 x, and r = 0,876.

A comparison of the snowpack water content on April 1 in the target area Lake Almanor and the control area gives: excess = 48%, probability = 0,0136, chances 1 : 73, the regression equation y = —3,36 + 0,684 x, and r = 0,951.

It appears that excesses in precipitation occurred in most of these areas. The objective in these projects is to increase snowpack for subsequent hydroelectric production.

10. Southern Cascades Area, Oregon.

This project has been under way for the past three years for a power company in the Southern Cascades in Oregon. The purpose of this program is to increase snowpack. During the three year period, over 5000 hours of silver iodide generation were recorded. Two of these years indicated positive precipitation effects and, during the last winter, the results were inconclusive. The effects of seeding operations derived from a comparison with the northern control area (regression equation y = —1,85 + 0,674 x, and r = 0,978) and with the southern control area (regression equation y = 6,60 + 0,688 x, and r = 0,745) are:

	target to northern control			target to southern control	
	excess	probability		excess	probability
1952.....	+ 21%	0,007	1952.....	+ 16%	0,244
1953.....	+ 24%	0,018	1953.....	+ 35%	0,151
1954.....	+ 6%	0,247	1954.....	+ 14%	0,331

11. Bitterroot Mountain Project.

A program has been under way in Eastern Washington and is on a continuing basis for a hydro-electric company since August 1951. The objective in this case is to increase rainfall during the late fall and early winter months in order to increase streamflow for the hydro-electric operations. In excess of 3000 hours of silver iodide generation have been recorded. Thirteen silver iodide generators comprise the network for an area of approximately 60 miles by 60 miles. From 8% to 29% excesses have been observed during the past year. In contrast, during 1952, the increases were only about 7%, whereas in 1951 excesses on the order of 30% were noted. The results for the year 1953 are shown in following Table:

	excess	probability	regression	r
Northern control	28%	0,132	y = 1, 10 + 1,06x	0,84
Southern control	29%	0,115	y = 3, 10 + 1,29x	0,86
Southwestern control	8%	0,339	y = 3, 36 + 1,19x	0,88

In this connection, it should be stated that the cloud seeding periods for this project for each of the previous years have been conducted for different months and, therefore, the three years operation cannot be shown on the same regression curves. The following table shows the data for previous years:

	time	excess	probability	r
Northern control	Oct. 1952—Feb. 1953	+ 4%	0,383	0,77
Southern control	„	+ 7%	0,346	0,59
Southwestern control	„	+ 10%	0,254	0,78
Northern control	Aug. 1951—Nov. 1951	— 11%	0,172	0,91
Southern control	„	+ 47%	0,032	0,83
Southwestern control	„	+ 39%	0,008	0,92

IV. Conclusion.

As a result of our massive seeding experiments of more than 50,000 hours during the last four years, we have concluded that precipitation excesses can be produced by using silver iodide smoke. The results from our own evaluations indicate these excesses to be on the order of 20% for extended time period [*15*]. We are of the opinion that much higher excesses can be produced for certain storm types and during the initial stage of the storm development.

In the Western United States we have had the greatest success with the storms displaying a cold vortex to great heights. We believe the instability associated with such disturbances to be the major factor for such success; however, it may well be that silver iodide being rapidly entrained in such systems has little opportunity to decay and, by virtue of the usually associated "cold" temperatures, it has a longer life cycle.

We have found from experience that pulsing the silver iodide smoke at the generator seems to be more effective than emitting a constant smoke plume. We do not entirely understand this phenomenon but believe that, by pulsing, a varying number of silver iodide particles may be produced, resulting in an optimum number of ice-forming nuclei most readily acceptable by the cloud system. Another hypothesis concerning pulsing silver iodide smoke is that nature itself, a convective cloud in particular, behaves in a periodic manner. The pulsing period we use most often is three minutes of silver iodide smoke in each fifteen minute interval. An exception is made during active cold front conditions when intense instability is present: silver iodide smoke emitted continuously appears to produce the most marked effect without any signs of "overseeding".

We are focusing increased attention to special storm types and to the convective cells within such systems. Radar may become the primary tool for carrying out this research. Our own efforts in this regard have been carried out by means of a 3 cm radar. During the past winter a small research effort was carried out with the use of radar and different concentrations of silver iodide smoke. A mobile APQ —13, 3 cm set was mounted

on a pick-up truck. It was sited at one of the Sierra Nevada target areas and operated during storms suitable for seeding. On occassion, lines of showers or fans of heavier precipitation have been observed downwind of a ground generator. In general, however, such phenomena are obscured by intervening cloud forms, and even when visible, are distorted by paralax. Tests showed that these phenomena are made visible in map form on the PPI scope. A generator was operated at 10 miles southeast of the radar site. A long line of echos developed downwind (to the north) from the site.

The efforts by our group have been confined almost exclusively to the problem of increasing precipitation. An equally large potential exists in the prevention of hail. In contrast to our industrial cloud seeding efforts which are applied on a broad scale basis, hail prevention may require intense local seeding efforts. For this application, radar seems ideally suited. Overseeding of the clouds seems the most obvious approach to this problem.

We believe that, as a result of the cloud physics and cloud modification programs in progress during the last ten years, meteorology has emerged from a purely diagnostic phase into the clinical and experimental stage leading to eventual localized weather control. As stated earlier, a close analogy exists between the medical profession and its attitude toward the early experimentalists such as PASTEUR and JENNER who introduced inoculation and vaccination, and the meteorological profession and its attitude toward modern cloud modification projects. Fortunately, as in the medical case, the statistics are now being collected which will give the right answers.

Acknowledgement.

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